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ON THE IMPORTANCE OF THE COMPONENT FAILURE RATE AND VESSEL STRATEGY OVER FLOATING OFFSHORE WIND FARMS O&M

TRABAJO FIN DE MASTER

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1 INTRODUCTION

In 2015, all United Nations Member States identified the 17 sustainable development goals that represent the key challenges for the sustainable development of our societies. Among them, referring to 7 and 13 goals, are ensuring access to affordable, reliable, sustainable and modern energy for all, while taking urgent action to combat climate change and its impacts [1]. At the same time, global energy demand and particularly electricity demand is expected to increase in the coming years, due to further development of emerging countries, and electrification of the transport and heating sectors [2]. This has led single countries and economic areas to set new ambitious carbon reduction targets on the path to net-zero by 2050. Offshore renewable energy technologies have a key role to enable these goals due to the vast available energy potential, which translates into an opportunity for the renewable sector.

According to Wind Europe Organization [3], 80% of the offshore wind energy resource in Europe alone is found in areas of water depths larger than 60 m, at which bottom-fixed solutions are not economically competitive. This represents 4,000 GW of resource potential in deep-water areas in Europe alone. Wind Europe expects offshore wind to produce 7% of the EU's electricity demand by 2030, with 4-5 GW of floating offshore wind installed until then [4]. In consequence, encouraging the development and deployment of offshore wind in deep waters is a key strategic issue. Conventional platforms such as semi-submersibles and spars have already been successfully deployed at prototype or pilot park scale, such as Hywind Scotland [5] (spar type), and Windfloat Atlantic [6] (semi-submersible type) up to water depths of 120m. With floating solutions, wind power can expand into new deep-water areas, often further from shore, opening vast new areas and markets currently unavailable for offshore wind. However, expanding into deeper waters is linked to some technical challenges, as some elements of an offshore wind farm become more expensive as depth increases. That is the case, for example, for mooring lines, anchoring systems, and dynamic cables. Sites further from shore also pose additional challenges for installation, and O&M activities. This is especially relevant in Spain, where the national marine spatial planning plans (POEM) set a significant share of the floating offshore wind areas in very deep waters (i.e. >250m in the North Atlantic area).

Throughout the last few years, the offshore wind industry has demonstrated to be highly competitive, taking a step forward in the development of new support platform technologies. The use of floating platforms is in the pre-commercial phase, it is paving the way to a broader market where the

depth of installation would no longer be a physical barrier. However, despite all the milestones achieved to date, offshore wind requires advanced solutions for better asset management.

A natural consequence of the rapid development of offshore wind energy is the necessary modernization of Operation and Maintenance (O&M) strategies, where equipment and auxiliary means must be managed following the highest Health and Safety (H&S) standards. Today, the offshore wind industry is making significant efforts to improve and optimize O&M strategies, especially for floating offshore wind platforms. In this way, it is necessary to incorporate advanced strategies to take into account the random nature of the atmosphere and ocean conditions.

O&M is crucial for offshore wind industry. In fact, last decade experience evidenced that accessibility rates have a significant impact over OPEX costs. Thus, O&M logistics will play a significant role in the cost of the energy produced by floating offshore wind farms because of the extra complexity added by the floating issue. Moreover, another extra of complexity of O&M is the wide variety of fails that will need to be faced during the lifespan of the offshore wind farm. Therefore, different support vessels, marine operations and port facilities will be required in response to the failure observed.

Moreover, the offshore wind industry is trying to improve and optimize the O&M strategy. That is way the need to incorporate advanced strategies to take into account the random nature of the atmosphere and ocean conditions. Usually, the O&M strategies are based on the definition of safety thresholds associated to specific metocean parameters (Hs, Wind intensity…). However, marine operations are usually highly non-linear processes where the risk assessment cannot relay over a simplified safety threshold definition. Understanding the interaction between the marine environment and floating structures is crucial for the safe operation of floating offshore wind farms.

An example is Ingeocean is an offshore wind farm O&M tool developed by a consortium composed by the Environmental Hydraulics Institute of Cantabria (IHCantabria) and Ingeteam Power Technology S.A., Service Division. Ingeocean is focused on the simulation of operation and maintenance (O&M) logistics for floating offshore wind farms. It couples long-term metocean databases, a digital twin of the wind farm (farm simulator) and advanced hydrodynamic numerical models to analyse different marine operations including: (1) personnel-transfer between vessel and floating structure, (2) workability on top of floating structures, (3) transportability between port and farm, as well as (4) marine operations associated to minor and major maintenance actions. This combination allows the

simulation of the marine operations associated to O&M from a long-term perspective (i.e. lifespan of a wind farm), including the optimization and risk-reduction related with the O&M operations.

From the experience acquired through the application of the Ingeocean tool, it has been possible to know that the O&M logistics has a strong impact over the wind farm availability. Differences about 5% between optimized and non-optimized O&M logistics have been evidenced. For example, it has been identified that the importance of the size of the CTV to be used (see Figure 1), something which is a balance between cost and availability. Many other parameters like the logistic time between alarm and mobilization, the boat landing orientation and position, may lead to extra 1% of availability losses in a floating offshore wind farm.

Figure 1. CTV performing a crew transfer manoeuvre.

Starting from exposed before, this work has the aim to reduce the uncertainties regarding the influence of the variability of the distribution of failure rates through the useful life.

In this work, Ingeocean O&M numerical tool has been used.

1.1 STATE OF THE ART

The most relevant models and tools are under continuous development, and in many cases are the result of scientific-technical research carried out in the framework of large international cooperation initiatives. These include major research centres and industry along the offshore wind value chain. Most of the models are variants of risk assessment methods based on reliability analysis and uncertainty quantification methods. They are used to model the relationship between availability, maintenance and cost, including the randomness of metocean conditions as a key variable.

Of the models reviewed, only one third of them are commercial, while the rest are authored models that are not publicly available as computational tools. Among the commercial tools, NOWICob, ECN O&M and O2M stand out. In general, all of them allow the modelling and simulation of the wind farm at the general aerodynamic level, considering several types of failures for each wind turbine. The model inputs consist of a description of the failure rates of the various subsystems or components of the wind farm, maintenance and repair strategies, and metocean conditions. The vast majority include stochastic simulations, such as Monte Carlo models, for the simulation of the faults. Each type of fault belongs to a certain category that determines the metocean constraints for its resolution in terms of the marine assets to be employed, as well as the time needed for repair, etc. Some models also track the availability of vessels, crews and spare parts, so that the influence of vessel and crew availability on overall plant availability and maintenance costs can be assessed.

Although there are multiple models and tools for offshore O&M, very few have been developed to the point where they are commercial products for sale on the market, largely due to the complexity of moving from models valid in academia to models that offer sufficient guarantees to make decisions of great economic and operational significance. The main challenges that an academic model faces in order to enter the range of consolidated industrial models are: (1) Lack of real information on failure rates, repair times and costs related to maintenance operations. (2) Lack of a correct market orientation as a consequence of limitations in market knowledge and (3) Lack of an integral vision that includes all the aspects related to the activities surrounding the operation and maintenance of a wind farm.

Most of the models identified have as their main objective the development of tools oriented to strategic analysis. Few tools cover all the time scales in which O&M decision needs arise, and few of them have a comprehensive approach and a commercial character.

NOWICob [19, 20, 21, 22, 23, 24]

- Main features: Discrete event Monte Carlo simulation model to estimate the long-term average availability of wind farms, operation and maintenance costs and other performance parameters.
- Main limitations: The model can be used to support strategic decisions regarding the profitability of a given wind farm project and to select O&M logistics solutions and other aspects of the O&M strategy. Its main limitation is that it does not have advanced offshore access and/or operations models.

ECN O&M [25]

- Main features: The O&M tool has been developed to analyse especially the O&M aspects during the planning phase of a wind farm.
- Main limitations: The tool is not a simulation tool. Instead, it uses long-term average data as input (failure rates, wind and wave statistics, costs, etc.) and generates long-term average values as output (costs and downtime). The tool is not intended to optimise logistical aspects.

O2M [26]

- Main features: Based on comprehensive databases of component failure rates and direct time to repair failures accumulated over many years from purchased and publicly available information.
- Main limitations: Tool capable of modelling entire wind farms, anywhere in the world. Its main limitations include. It does not have an advanced model for simulation of offshore operations.

MERMAID [27]

- Main features: Classical weather windows model highly oriented to the statistical analysis of operating windows.
- Main limitations: Model capable of modelling O&M strategy, but lacking advanced models for accessibility and workability analysis on floating wind platforms.

None of the models presented above implement variable failure rates using bathtub curve distribution.

In most studies concerning O&M simulation of offshore wind turbine components, constant failure rates for each turbine component [28] are being used. However, it has been shown that any component, whether in the wind industry or not, has a failure rate described by a bathtub curve [14, 29]. This curve requires a deeper knowledge of the individual components, which makes it difficult to apply in this field due to the relatively recent emergence of the wind industry and offshore platforms.

In some of the cases the database used for the research came in a huge percentage from onshore wind farm. Mixing offshore and onshore measurements it is positive for increasing the amount of data but it is not desirable because it has been exposed that failure rates of OWF are much higher than in the onshore wind sector. Something which might be expected taking into account the harder weather conditions [16, 17].

1.2 AIM OF THE PROJECT

The offshore wind industry is an emerging and still developing sector, specially floating offshore wind. Initially, all the research was focused on design, leaving aside the O&M field. It has been found that O&M accounts for 30% of the cost required for the establishment of an Offshore Wind Farm [7], so it is necessary to undertake as much research as possible to enhance the understanding of this field in order to minimise the uncertainty when planning the logistics of a wind farm.

According to these ideas, the present project aims to depth into two key factors with an strong influence over the technical-economic feasibility of a wind farm: (1) the number of O&M vessels required per wind farm given the randomness associated to the component failure and (2) the importance of components' failure rates over the feasibility of an offshore wind farm.

1.3 CONTENT

The present Master Thesis is organized as follows:

Section 2. Methodology. On this section the scientific basis and methodology of the present Master Thesis are described.

Section 3. Model description. The present section describes the numerical model used, named INGEOCEAN developed by IHCantabria and INGETEAM Power Services

Section 4. New Contributions. This section summarizes the scientific contributions proposed by the Master Thesis Candidate together with IHCantabria researchers which has been implemented a new version of INGEOCEAN .

Section 5. Results. This section summarizes the results achieved. It includes the definition of a base case, the sensitivity analyses performed and finally the outputs of the model.

Section 6. Conclusions. Finally, a set of conclusions have been drawn as a synthesis of the research carried out.

Section 7. References.

1.4 ABBREVIATIONS

- OWF: Offshore Wind Farm
- CTV: Crew Transfer Vessel
- LM: Light Maintenance
- MM: Medium Maintenance
- HM: Heavy Maintenance
- OPEX: Operating Expenses

2 METHODOLOGY

As stated at the beginning, the aim of this project is to carry out a technical-economic feasibility analysis to study in detail two key factors of the O&M such as the number of O&M vessels and the variability of the components' failure rates.

The analysis was conducted thanks to a numerical model named INGEOCEAN. INGEOCEAN is a numerical model focused on the simulation of operation and maintenance strategies for offshore wind farms, bottom fixed or floating wind farms. The O&M (Operation and Maintenance) simulator takes the meteocean data at the selected location, as well as the definition of the wind farm and its logistics. INGEOCEAN provides multiple outputs that will help to understand the behaviour of the simulated scenario.

By varying the input parameters of the O&M fleet size and the failure rates of the components (sensitivity analysis); it is intended to study their impact on the outputs provided by the model. This will led to conclusions on the importance of the role of these parameters in the development of O&M research.

Figure 2 summarizes the methodology proposed which combines well know techniques like sensitivity analysis together with new implementations on the numerical model required to leverage the simulation to higher levels of realism.

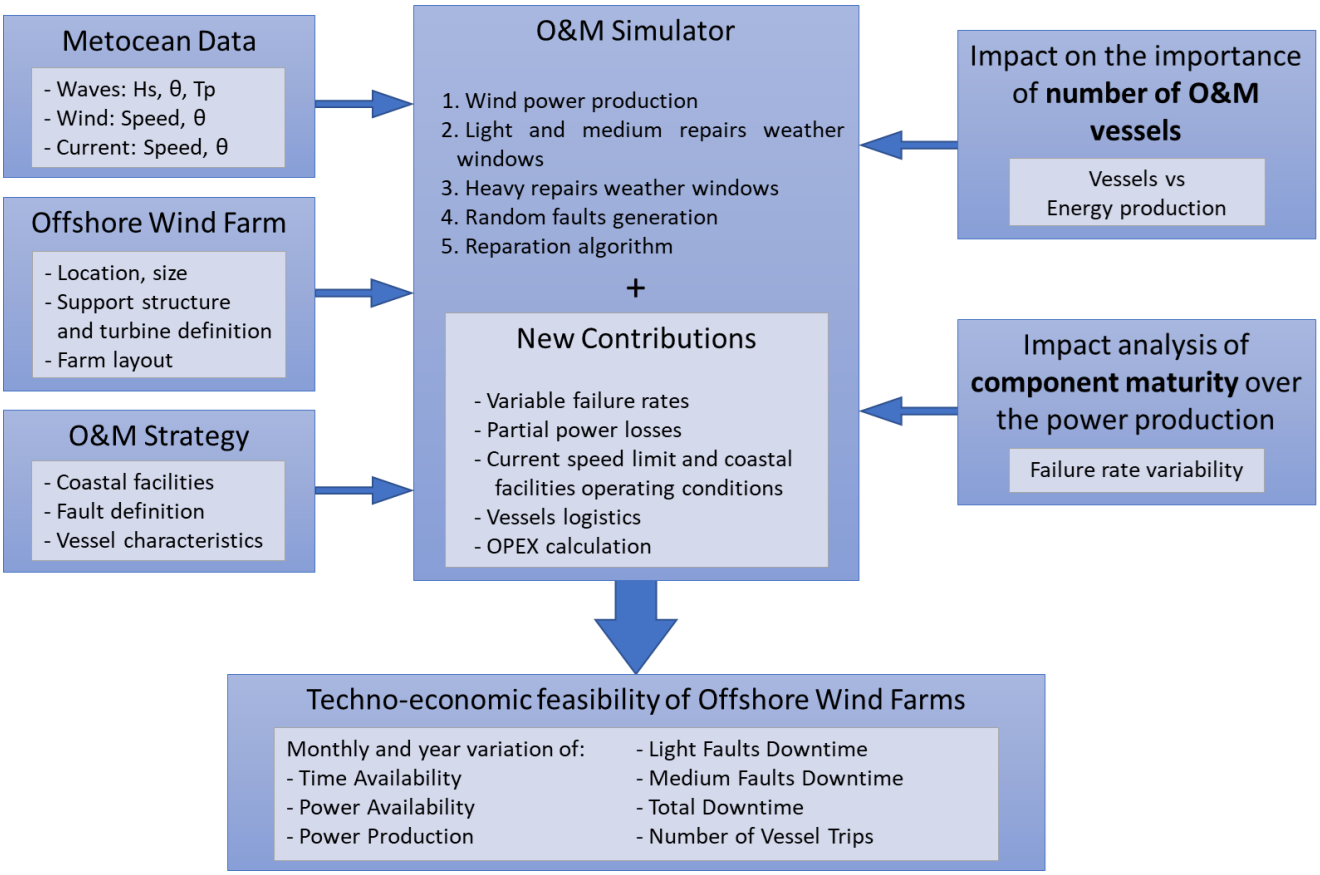

Figure 2. Methodology.

3 MODEL DESCRIPTION

The model is divided into five modules or blocks, which predict the behaviour of different components or systems of the offshore wind farm during its lifetime. Next it can be seen the list of subsystems included in INGEOCEAN.

- Wind power production (See section 3.1)
- Light and medium repairs weather windows (See section 3.2)
- Heavy repairs weather windows (See section 3.3)
- Random faults generation (See section 3.4)
- Reparation algorithm (see section 3.5)

3.1 WIND POWER PRODUCTION

The objective of this block is to compute the farm power production along the lifespan of the asset on an hourly basis. To do so, the module processes the metocean data file for a particular location, which includes wind direction, wind speed at hub and significant wave height.

Taking into account the type of turbine provided by the user and the associated thrust and power curves the simulator computes the power production per turbine. For this purpose, the module analyses for every hour of the meteocean record if the wave height is below the operational limit and whether the wind speed is between the cut-in and cut-out of the turbine.

The wind production block also considers the turbines wake effect, based on Jensen model [8, 9], which takes into consideration the wind direction, the rotor radius, the relative positions of the WTGs (Wind Turbine Generators), the tail decay coefficient and the thrust curve. With these specifications, the incident wind speed can be corrected for the turbines located behind the tail of others.

This module also performs a directional analysis of the winds and waves measured at the wind farm location. It is displayed as output as well as the inter-annual and intra-annual analysis of energy production variability. The hourly time series is saved for later use in the execution of the last module in which the real power production of the wind farm is calculated.

3.2 LIGHT AND MEDIUM REPAIRS WEATHER WINDOWS

The light and medium repairs accessibility module finds all the windows in which is possible to work on site for the different fault types. In order to do so, the interaction between platform and vessel has to be analysed numerically. The methodology here proposed can be found in [12] and [13]. The methodology to be followed in this module is summarised in the next four main step: (1) RAO of CTV-floating platform system, (2) Operational limits estimation, (3) Transportability validation and (4) Weather windows analysis.

1. **RAO of CTV-Floating platform system**. On this first step the coupled hydrodynamic system composed by CTV and PLATFORM is analysed by means of a potential frequency domain hydrodynamic model when both are in crew transfer position. The procedure develops as follows:
    a. The inertia matrices (M), hull geometries, mooring system description and fender/ boatlanding positions are obtained from the vessel and platform designers.
    b. Use a BEM (Boundary Element Method) frequency domain model to calculate the added mass (A(ω)), radiation damping (B(ω)), hydrostatic stiffness matrices (G_B) and the waves excitation forces (F(ω,θ)), where ω is the angular frequency and θ is incident wave direction. In this case, SESAM from DNV was used. Figure 3 displays the detail of the used mesh.

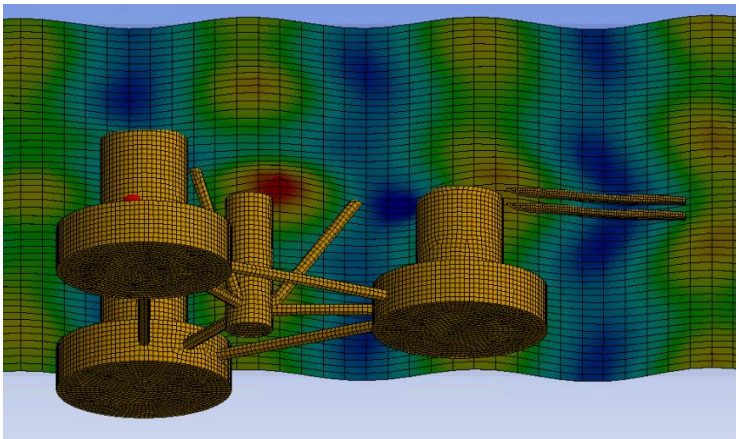

Figure 3. Detail of the mesh of the platform and vessel system for the BEM simulations.

c. Linearize the mooring system using a FEM (Finite Element Method) model by means of off-set numerical tests, obtaining a moorings stiffness matrix (G_M) for the platform (the vessel has no moorings). Again, SESAM software was used.

d. In order include a more realistic dynamic performance of the system from the hydrodynamic point of view, linear hydrodynamic coefficients have been included into the system. They represent the viscous drag not covered by the potential flow solver. The computation of the viscous damping matrices ($B_V(\omega)$) of the vessel and the platform have been carried out as a percentage of their critical damping matrices.

$$B_C(\omega) \;=\; 2 \cdot \left[diag\big(M + A(\omega)\big) \cdot diag(G_B + G_M)\right]^{\frac{1}{2}}$$

e. Construction of a time domain simplified model of the platform standing alone, without external forces to calibrate and validate the hydrodynamic coefficients.

f. Once the hydrodynamic coefficients are in place, a frequency domain model based on Ogilvie is built including the mechanical interaction between the fender and the boat landing, matrix (D):

$$\begin{bmatrix} K(\omega) & D' \\ D & 0 \end{bmatrix} \cdot \begin{bmatrix} R \\ \Lambda \end{bmatrix} = \begin{bmatrix} F(\omega,\theta) \\ 0 \end{bmatrix}$$

where:

$$K(\omega) = -\omega^2 \cdot \begin{bmatrix} M_1 + A_{11}(\omega) & A_{12}(\omega) \\ A_{21}(\omega) & M_2 + A_{22}(\omega) \end{bmatrix} + \cdots$$

$$\ldots + i \cdot \omega \cdot \begin{bmatrix} B_{v,1} + B_{11}(\omega) & B_{12}(\omega) \\ B_{21}(\omega) & B_{v,2} + B_{22}(\omega) \end{bmatrix} + \begin{bmatrix} G_{B,1} & 0 \\ 0 & G_{B,2} + G_M \end{bmatrix};$$

$$R = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix};\;\; \Lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix};$$

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & -Z_1 & Y_1 & -1 & 0 & 0 & 0 & Z_2 & -Y_2 \\ 0 & 1 & 0 & Z_1 & 0 & -X_1 & 0 & -1 & 0 & -Z_2 & 0 & X_2 \\ 0 & 0 & 1 & -Y_1 & X_1 & 0 & 0 & 0 & -1 & Y_2 & -X_2 & 0 \end{bmatrix};$$

This equation solves the dynamics of the vessel-platform system imposing, by means of matrix D, that the position of the fender (in the vessel local frame $[X_1,Y_1,Z_1]$) and the position of the boat landing (in the platform local frame $[X_2,Y_2,Z_2]$) are the same. Moreover, Λ is a vector containing the forces in the x, y and z directions. This vector is applied at the contact point and it is required to

keep both sides, vessel and boat landing, together. By solving the Ogilvie equation for all angular frequencies and incident wave directions, leads to a response amplitude operator (RAO) [10].

2. **Accessibility and workability validation**. Based on personnel transfer RAO obtained in the previous step, operational limits for crew transfer and workability are checked. A wave-by-wave analysis was applied to each sea state of the lifespan. The steps followed to analyse operability are shown below:
    a. For each sea state, the metocean database is used (i.e. significant wave height, peak period, peak enhancement factor and directional spreading factor) to build a wave spectrum which will be the base for a random time series reconstruction. Then for each sea state, first the free surface time series is checked to see if it meets realistic statistical requirements. Then, the time series for the 15 degrees of freedom (6 movements for the vessel, 6 movements for the platform and 3 forces on the contact point) are reconstructed [11].
    b. Once each sea state has its corresponding 15 degrees of freedom time series, they will be checked to validate if they meet the operational limits for workability and transferability. The criteria used in this process are as follows:
        i. Vertical and horizontal RMS accelerations on hub must be below the limit.
        ii. Relative RMS rotations between vessel and platform must be below the limit.
        iii. Static friction force at contact point must be enough to stand the computed forces (CTV thrust force and friction coefficients are needed) during minimum consecutive time intervals, and for a minimum percentage of the total time.

    It is assumed that transferability must be possible, during all the working time for security reasons.
    c. Steps a) and b) above are not necessary if for the type of reparation being studied, and current sea state, the wind speed or the wave height are above the limit. For repairs involving lifting there is a lower wind speed limitation. Wave height is also limited by the wave breaking limit.
3. **Transportability validation**. The transportability limits for all lifetime hours are checked against the given constant wind speed and wave height constraints. For this purpose, several

nodes along a transport route are taken from the climate database of IH Cantabria and the transport time is computed and rounded up. (For example, even if the transport takes just 20 minutes, an hour is considered as the transport time). This is a conservative assumption based on the fact that the model works with a discrete hourly time series.

4. **Weather windows analysis**. It combines transportability and workability to find all the possible weather temporal windows in which technicians can be working on the platform. This is done by assuming that if transportation is possible before and after a workability window, then the whole time of the workability window is available.

Finally, the analysis of the inter-annual and intra-annual variation of the different workability, transportability and accessibility (combination of workability and transportability) is presented. Additionally, the weather windows obtained are registered in a file that will be later used in the fifth module of the simulator.

3.3 HEAVY REPAIRS WEATHER WINDOWS

This module computes the windows for all main steps described in the Heavy Maintenance Method Statement. This file contains all the steps and sub-steps of the heavy fault repair process with their respective wave height, wind speed and current speed limitations as well as the activities duration and whether the sub-steps need to be consecutive or not. If a main step is composed of several consecutive sub-steps, it checks if it is possible to perform all the sub-steps without pauses among them. It is possible to perform a sub-step if the metocean conditions are below the limits during a number of consecutive hours equal to or greater than its duration. The port reparation is considered as one main step more, which is not compulsory to perform in one single action: if the wind conditions at port were too high, the workers would stop repairing and wait until it is possible to start again.

Once this is done, the module also combines all main steps and the logistic time (time from protocol activation to the beginning of the first step) to find how long would it take to repair a heavy fault. The duration will depend on the time of occurrence and will be neglected in case of interaction between heavy faults (this will be done later in the reparation algorithm, using the weather windows of the main HM steps computed in this block). This is used to return the inter-annual and intra-annual variation analysis of the HM repair time and weather downtime, and it is also used later in the random

faults generation method to avoid new faults starting during heavy reparation. The reason to compute reparation time in this module and not in the algorithm is that in the fourth module would not be enough HM faults for good statistics, and the interaction among HM faults can be neglected because the probability of the HM faults interacting during a lifetime is low.

3.4 RANDOM FAULTS GENERATION

This block randomly distributes all types of faults in the turbines and in time. It computes the number of faults for a certain type as the product of the fault rate, the number of years in the lifespan and the number of turbines. This rate is constant in time and the same for all the turbines. If the resulting number is not an integer, the algorithm may randomly assign one more fault with a probability equal to the decimal part of the resulted number. Then, it randomly assigns to each fault an initial instant along the lifespan and a turbine. Finally, the result is post processed to avoid faults coinciding on turbines under heavy maintenance operations, using the output from the previous block. The faults are sorted first by type: heavy-medium-light, and the chronologically, which is needed for the next and last module.

3.5 REPARATION ALGORITHM

The reparation algorithm is the core of the model, and it represents the Operations and Maintenance part of the system. For each simulation of the lifespan, it computes when all the faults are repaired, obtaining the time that the turbines are not available for production, the number of trips and the downtime. The algorithm is described on Figure 5. The main aspects considered for the simulation were:

1. There can only be one offshore crew working per weather window for light and medium repairs.
2. If the medium CTV is activated, coetaneous light faults will be fixed with the medium CTV.
3. If the medium CTV is not activated, light faults are fixed with a light CTV.

4. If there is time to work in a second fault during one weather window, after finishing the first fault reparation, that time will be used.
5. If a medium fault and a light fault coincide, the medium fault will be fixed first.
6. If a heavy fault appears in a turbine with a light or medium (LM) fault, before the LM fault reparation started, the LM reparation is assumed to be performed during heavy reparation, unless the LM fault implies a switchgear malfunction that affects other turbines. In that case the LM fault is repaired as usual.
7. If a fault takes place on a turbine under HM, it will be ignored.
8. If a heavy fault appears while HM is already ongoing in the park, its reparation must start after the ongoing HM is finished.
9. If a CTV is already activated, there will not be the need to wait the logistic time before using it.

For this study, it has been determined that repairs will only be carried out with the medium vessel and in none of the cases considered will include any specific vessel for light faults. This decision was taken to simplify the scenario and reduce the number of variables in the system.

To obtain the outputs of this block, all the simulations are averaged (it should be highlighted that 40 lifespans have been simulated per sensitivity case), and the inter-annual and intra-annual variation analysis of the following variables is presented:

- Time based availability (using wind-in/out-limits definition).
- Production based availability.
- Weather downtime for light faults, medium faults, and both combined. This will be defined as time that it took to repair divided by the ideal repair time. It is given as a percentage, where 100% implies no extra downtime, it is observed because of metocean condition reasons.
- Number of offshore trips for the light and medium CTVs, port-to-site and site-to-port are considered two different trips.

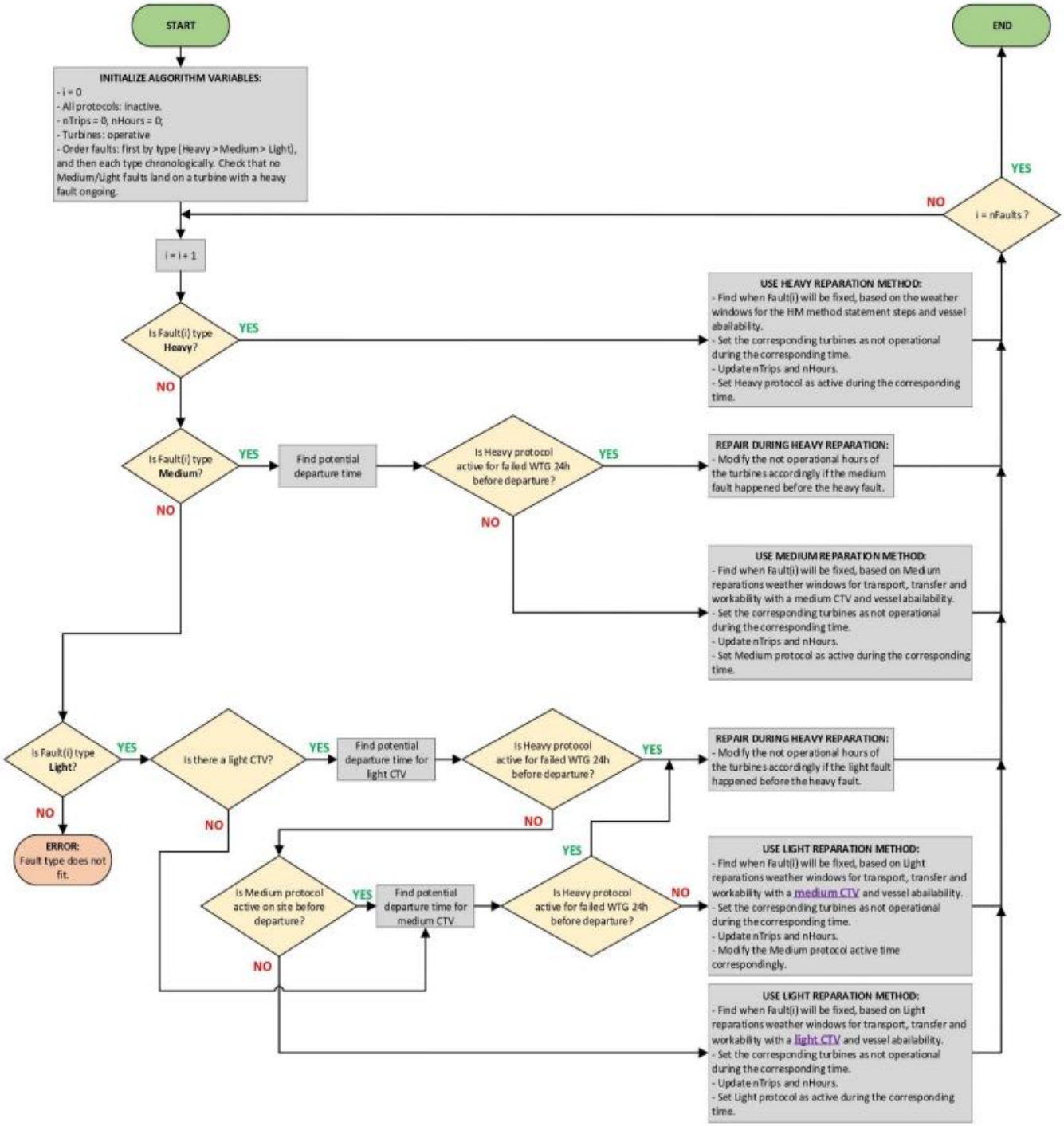

Figure 4. Faults repair algorithm.

3.6 MODEL LIMITATIONS AND ASSUMPTIONS

In this section, the main limitations of the model are listed and described.

1. Some operational limits are considered constant or dependent on a unique parameter.

   In the case of power production, CTV transport or for all main steps in the heavy maintenance method statement, only wave height has been used as the unique limiting parameter for wave excitation, which has been considered as a constant limitation along the whole lifespan. Therefore, for those cases there are not influence of wave period, direction, peak enhancement factor or directional spreading. Usually this implies choosing values with a security margin, making the results conservative. Wind and current speed are also considered.

2. Limitations of the crew transfer and workability operational limits model.

   The dynamic model implied some assumptions:

   i. The hydrodynamic coefficients are based on the potential flow theory and neglect viscosity effects.
   ii. Solving the dynamics in the frequency domain implies linearizing all forces, reducing the accuracy of the model (i.e. mooring system).
   iii. The calibration performed of the only implied numerical decay tests. Ideally, the model should be calibrated using experimental data of static offsets, decays and regular waves.
   iv. The model ignores the coupled influence of wind and currents, which are considered independent and have their respective constant limiting factors.
   v. Overall, these limitations imply using a safety margin which may make the model less optimistic than reality, but it is still better that considering a constant limiting wave height.

3. Transport time is considered longer than it is. This was already explained in step 3 of Section 3.2. It makes the model more conservative.
4. Faults are distributed uniformly, not depending on aging of components or on metocean conditions variability. This can be considered an optimistic assumption.
5. Some faults may be ignored due to heavy maintenance.

The fault generation algorithm avoids setting faults on turbines that are under heavy maintenance, considering no interactions between HM faults. During the repair algorithm, HM faults may take longer than expected due interaction with other HM faults. Consequently, some faults may land on turbines under HM reparation. These faults will be ignored. This implies less faults and therefore a model slightly optimistic than reality. The probability of this kind of events happening was estimated, and the impact over the results was found to be negligible.

6. The priority of repair of switchgear faults is not considered.

   In reality, if a fault on the switchgear is produced and it implies more than one turbine stopping, then fixing that fault would have top priority. In the model, the priority of fault reparation does not consider this. This means that, sometimes, the turbines will be stopped slightly longer than they should when the vessel is not available to fix the switchgear fault because it is repairing a previous fault. This makes the model some more conservative.

7. The preventive maintenance is not considered in the algorithm.

   Although its potential impact on the availability is evaluated, the interaction with the corrective maintenance is neglected.

Overall, with all the assumptions made, the idea during the project was to make the model as realistic as possible, but always making sure that, in those cases where some assumptions need to be made, the results are more conservative than reality, but never more optimistic.

3.7 PREVENTIVE MAINTENANCE IMPACT ANALYSIS

Although the preventive maintenance is not included in the algorithm, the analysis of the minimum potential impact on the availability have been performed. With this purpose, the following considerations where taken for the preventive maintenance impact over the wind farm availability:

- Preventive maintenance operations are performed:
  - During June, July, August and September.
  - During daylight.
  - With significant wave height lower than 1.5m.

  - If possible, when the wind speed is below the cut-in limit.
  - There is a minimum working time.
- Preventive maintenance operations duration takes 40h every year, which do not need to be performed consecutively, and the turbines do not stop between operation days.
- Corrective maintenance does not limit the resources for preventive maintenance.

Using these considerations, the number of available hours below the cut-in wind speed were computed and compared with the number of operation hours, finding that there are not enough "below cut-in hours". Then, the number of hours inside the production zone needed was calculated, as well as the production losses during those hours. This has been done for different minimum working times. The results are presented on Table 1.

Table 1. Preventive Maintenance impact on availability

Minimum working time	Time based availability loss	Energy based availability loss
2 h	0.05 %	0.00004 %
4 h	0.37 %	0.00015 %
6 h	0.78 %	0.00100 %
8 h	1.04 %	0.00200 %

The results for time-based availability loss are larger than the results for energy-based availability loss. The reason for this is that, although the production time missed due to preventive maintenance operations is significate, the production for that time is low because the wind is close to the cut-in speed.

Considering the low impact on the energy-based availability found, even if it increased in reality due to interaction with the corrective maintenance, it could be assumed that the error of neglecting preventive maintenance on the algorithm will be negligible. The same applies to the floater preventive maintenance, which takes two days every 5 years on the lifespan (that is three times), and, in the worst-case scenario, would imply a time-based availability loss of 0.08%.

4 NEW CONTRIBUTIONS

The immeasurable nature of variables in the O&M field bring the model the opportunity of being in constant development. During the studying process of the simulator, certain limitations in the model were highlighted. In the course of this master's thesis, it has been attempted to implement those that have been considered most relevant.

All the contributions explained below were implemented but it has been necessary to disable some of them for the correct performance of the analysis discussed in this project.

4.1 VARIABLE FAILURE RATES ALONG THE LIFESPAN

One of the improvements implemented and which have also been incorporated in this thesis is the capability of defining a different failure rate for each year of the lifespan. Previously, the model allowed defining different failure rates for each of the defined fault types, but this failure rate was unique and constant throughout the entire service life.

Several studies in industrial engineering have shown that components experience an increase in failure rate at the beginning and at the end of their lifetime in such a way that the failure rate describes a bathtub curve.

Unfortunately, the short period of time that the offshore wind sector has been in operation leads to a high degree of uncertainty in this field. Although it is not possible to carry out the same research using data exclusively from offshore wind farms, the limited data that have been recorded so far suggest that the same failure rate trend is also applicable to this sector.[14]

Even if the exact curve describing the failure rate over the lifetime of the turbine is not clear, what is certain is that for most components this rate will not be constant, so in order to try to faithfully represent reality it is necessary to have several failure rates.

For this reason, we have included among the programme inputs in the fault setting section the opportunity to choose whether we want a variable or constant failure rate. In the case of choosing a constant ratio, only a single annual failure rate will be assigned to this fault type, which will be applied throughout the entire lifespan, while choosing a variable ratio it will be necessary to include a value for each year of the lifespan for which it is desired to design.

After that in the fourth module, Random Fault Generation, once the model is working, the program distinguishes between those faults defined by a single value or by several fault rates.

The main difference is the way in which the faults are estimated. In the first case, it starts by calculating the total number of faults that will occur over the lifetime and distributes them randomly, while in the variable case, the reading and distribution of the faults is done annually, again randomly with a fault occurrence probability equal to the annual failure rate.

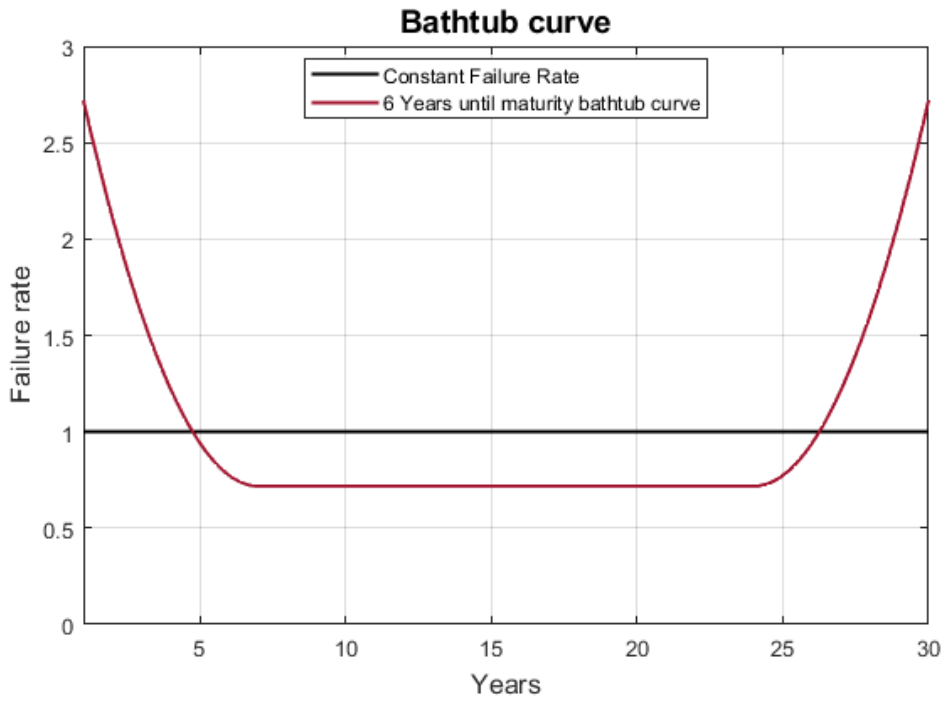

Figure 5. Example of a common distribution of failure rates along lifespan.

4.2 PARTIAL POWER LOSSES

Some of the tasks in the O&M field do not lead to power loss or simply to a partial reduction in production. These types of faults do not affect the power production but it is not possible to exclude them from the system because they are time consuming as they have a significant impact on the vessel availability as they still require maintenance to be carried out.

Before this thesis, all the failures that were introduced in the faults section were associated with a total shutdown of the turbine from the time the fault occurred until it was repaired and therefore the downtime value was extremely important as it implied large losses.

With the updated version of the system, a new field has been added in the inputs which specifies the power loss produced by each of the failures in such a way that if a failure causes the shutdown of the turbine, the power loss will be 100% and if its production continues without suffering any losses, it will be 0% (with the possibility of taking intermediate values). In this way, the less relevant but more frequent faults will not produce an unrealistic drop in availability but will allow us to carry out the simulation of those tasks that affect the availability of the vessel.

4.3 CURRENT SPEED LIMIT AND COASTAL FACILITIES OPERATING CONDITIONS

Another constraint identified was the lack of current speed limitation for O&M. In addition to wave height and wind speed restrictions, it is also necessary to take into account the current speed as it limits both repair time and transport. There are certain locations in the north sea, such as Saint Brieuc, where current velocities may prevent to conduct any marine operation during certain periods of the tide time series. For this reason, it was included a current speed limit for light vessels and another one for medium vessels, and a new condition was added to the model so that when checking whether it is possible or not to go out to carry out a repair, the current data is also checked.

Another limitation within the metocean domain detected was wave periods. They may has strong influence when natural resonance periods of the elements involved on the marine operations are affected. This was not being considered. As in the case of currents, a new restriction was enabled for the resonant periods.. The only difference with the currents is that it is not a value acting as an upper limit, but rather specific values to be excluded from the series of valid periods.

4.4 VESSEL LOGISTICS

As already explained in the model performance description, specifically in “Module 5: Repair algorithm, there are three possible fault categories: heavy, medium and light. These categories refer to the difficulty of repairing the fault, since the more complex the fault, the more sophisticated the vessel required. According to the protocol established in module 5 and shown in Figure 4, light faults will be repaired either by the light vessel or by the medium vessel in case it is operating.

Based on previous experience and contact with stakeholders, it has been concluded that the possibility of exchanging vessels is not always possible. For this reason, a new protocol was created in which each category has its own vessel and maintenance is carried out separately for heavy, medium and light faults. Therefore, the module was modified to include all three types of protocols in accordance with the user's request:

- A single vessel type that will repair light and medium faults.
- Two types of vessels for the two categories, which are not independent.
- Two independent vessel types for light and medium categories.

In order to simulate construction or heavy long-distance repairs, the option of a second port for this type of operation has been included, considering the possibility of having a fabrication port and an assembly port in the case of simulating the construction process.

4.5 OPEX CALCULATION

The simulator generates as outputs the required indicators to understand the behaviour of the Offshore Wind Farm, but it does not have a specific module for the economic analysis of the OWF. A critical factor when deciding on the implementation of a project is the economic feasibility analysis, the calculation of the Net Present Value (NPV) and other similar indicators is very necessary for a good decision-making process.

In this case, this limitation was detected and a new algorithm for calculating O&M related costs was developed. In this algorithm, the characteristics of each of the vessel types used are inserted, including the type of contract, mobilisation fee, transit speed, fuel consumption at both standstill and on transit, the cost of the replacement pieces and the personnel costs. Then the previously calculated simulator outputs are entered. These include the number of trips made and the downtime taken to repair each of the faults. These are the main factors used to calculate the OPEX (the costs derived from O&M).

On the other hand, with the calculation of the real annual average power production and the price per MWh entered, the Net Present Value balance is calculated, which helps us to evaluate the viability of an investment.

In this project, an OPEX calculation has not been carried out, as the values to be entered are extremely variable and depend on the type of vessel, type of contract, operating costs, etc., and would not be particularly representative. Instead, an analysis of the benefits has been carried out based on the increases in energy production with the increase in the number of vessels.

5 RESULTS

5.1 BASE CASE

5.1.1 WIND FARM DESCRIPTION

For this project, it has been decided to choose a wind farm under development with the aim of making it as up-to-date as possible, considering a turbine size in accordance with the latest technologies.

Therefore, a wind farm in the early-planning phase on the coast of San Cibrao, Galicia was chosen.

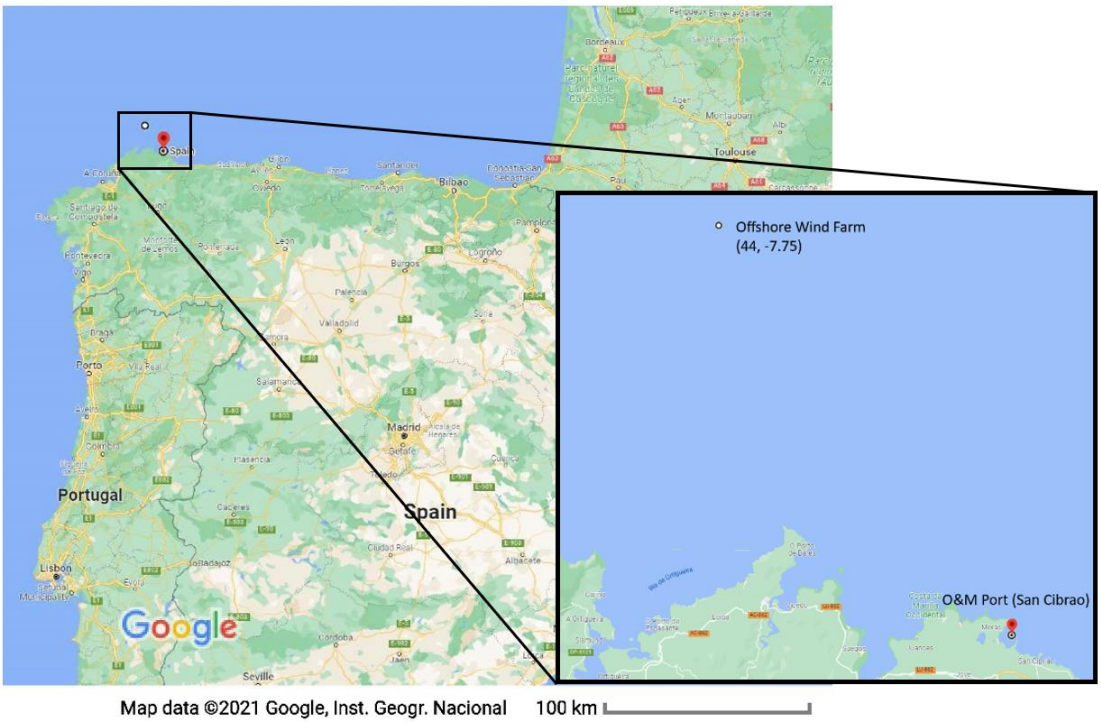

Figure 6. Site location. Source: Google Maps

The location of this site is at coordinates 44, - 7.75. This area is one of the most suitable for the construction of an offshore wind farm in Spain as the continental shelf maintains acceptable depths for floating wind turbines (170 m) at a relatively close distance from the coast (the O&M port is about 40 km away). In addition, Galicia is also one of the most windy areas of the Iberian Peninsula. It receives a lot of wind from the Atlantic Ocean in a SW direction, which does not reach the rest of the Cantabrian

coast, since Galicia acts as a windscreen. At the site location, the average wind speed measured is 9 m/s.

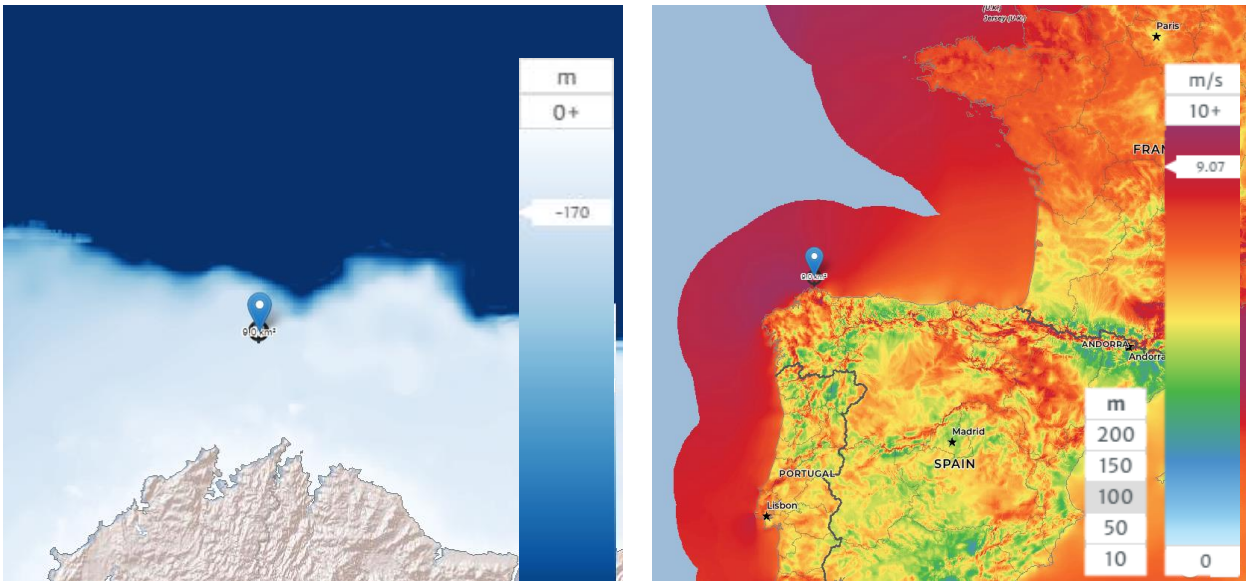

Figure 7. Water depth (left) and mean wind speed (right) at site. Source: Global Wind Atlas

As mentioned above, a floating offshore wind farm is planned at coordinates 44, - 7.75 and the port of San Cibrao, 40 km from the site, will be used for operation and maintenance activities. For the installation of the turbines, a floating platform OC4 semi-submersible designed by the National Renewable Energy Laboratory (NREL) has been defined.

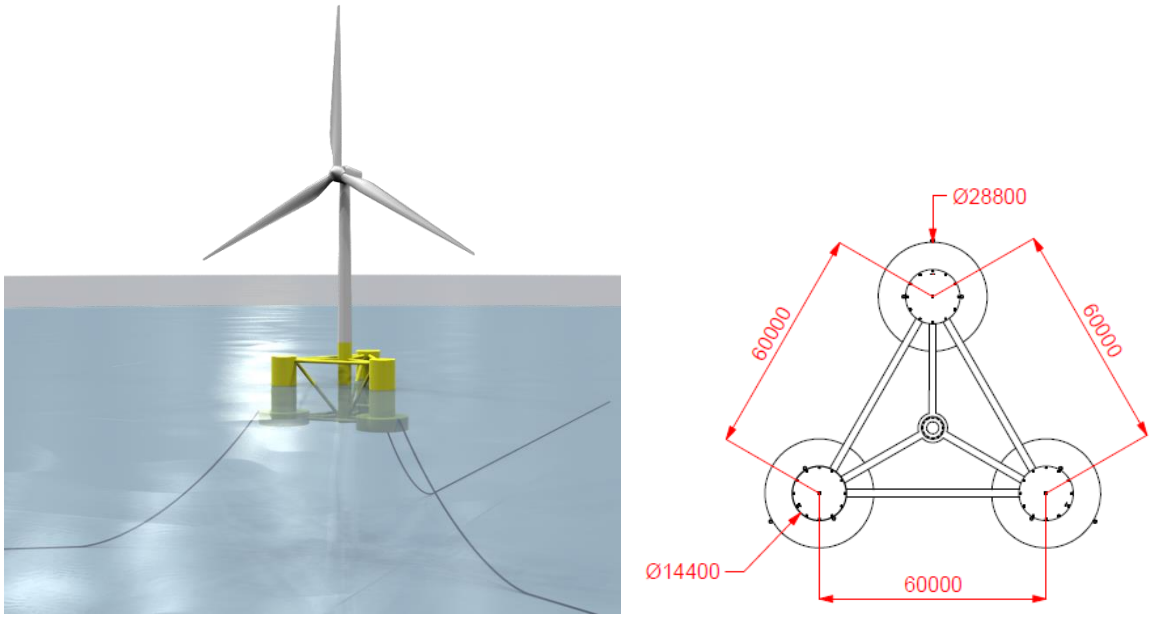

Figure 8. Full OC4 semi-submersible platform with its wind turbine.

Table 2 displays the mass properties of the TRL+ platform, also, Figure 9 shows the lay out of the mooring system considered.

Table 2. TRL+ theorical mass properties.

TRL+. Semi-submersible Platform	
Mass matrix	**Prototype scale**
Mass (Kg)	23200227.53
COG X [m]	0
COG Y [m]	0
COG Z [m] *	13.88
Ixx [Kg*m2]	35075863844
Iyy [Kg*m2]	35336162755
Izz [Kg*m2]	27878483328
***COG Z from keel**	

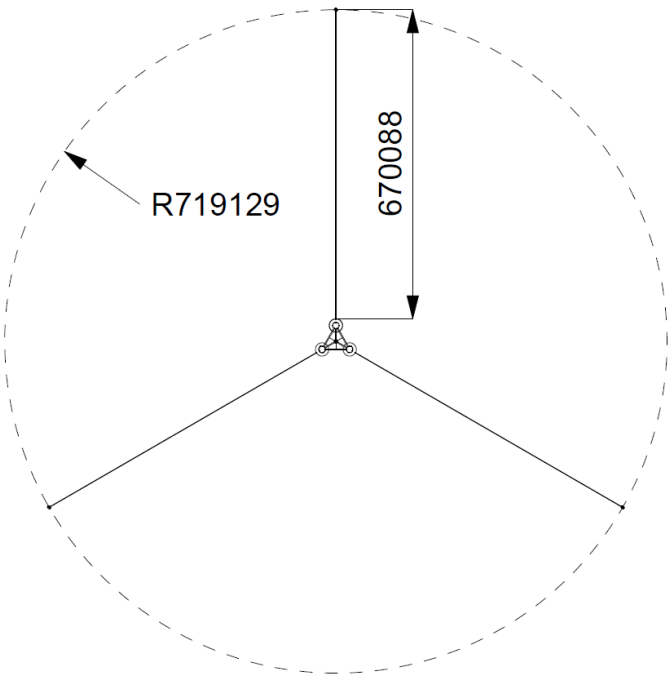

Figure 9. Top view of the mooring system.

The OWF will have 30 turbines of 15 MW each. This type of turbine has a hub height of 150 m and 120 m of rotor radius [15]. The power curve associated with this type of turbine is as follows:

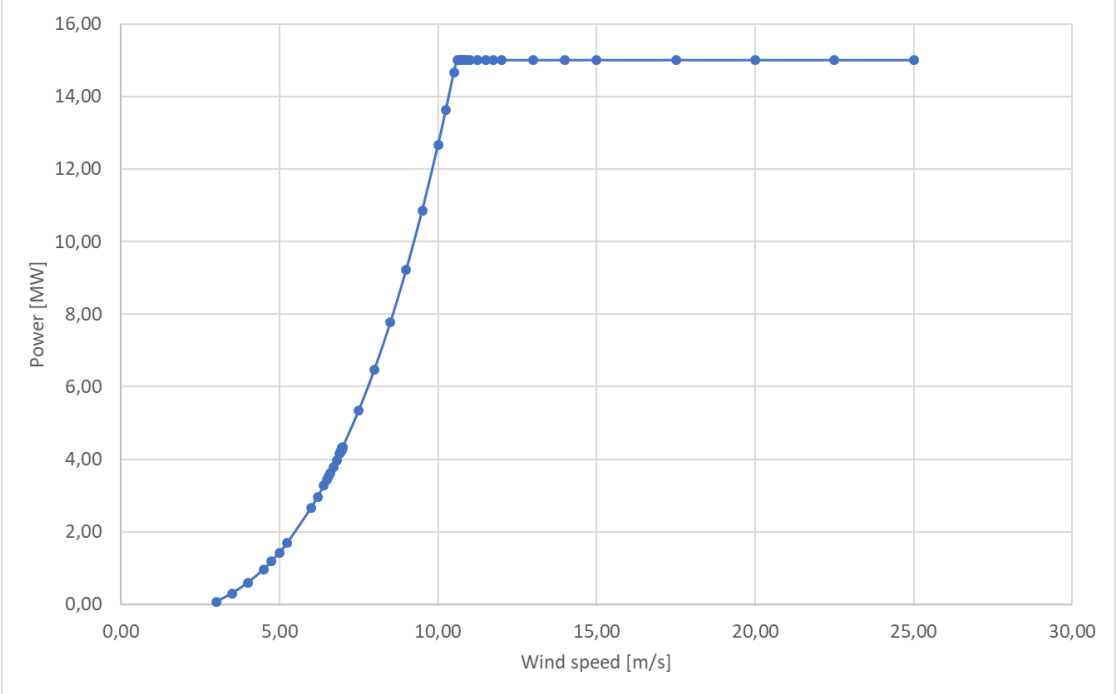

Figure 10. 15 MW Turbine Power curve. Source: [15]

The cut-in and cut-out of this turbine model are 3 m/s and 25 m/s respectively and the significant wave height limit for operation is 8.5 m.

The turbines will be distributed in a regular 3 x 10 grid. Initially, a 5 x 6 grid was planned, but during the operation of the turbine, the wakes of the first rows decreased the wind that reached the fourth and fifth rows, so it was decided to use a 3 x 10 layout oriented 50 degrees east in order to improve its interaction with the wind. This the orientation was selected with the purpose of maximising production towards the most likely wind.

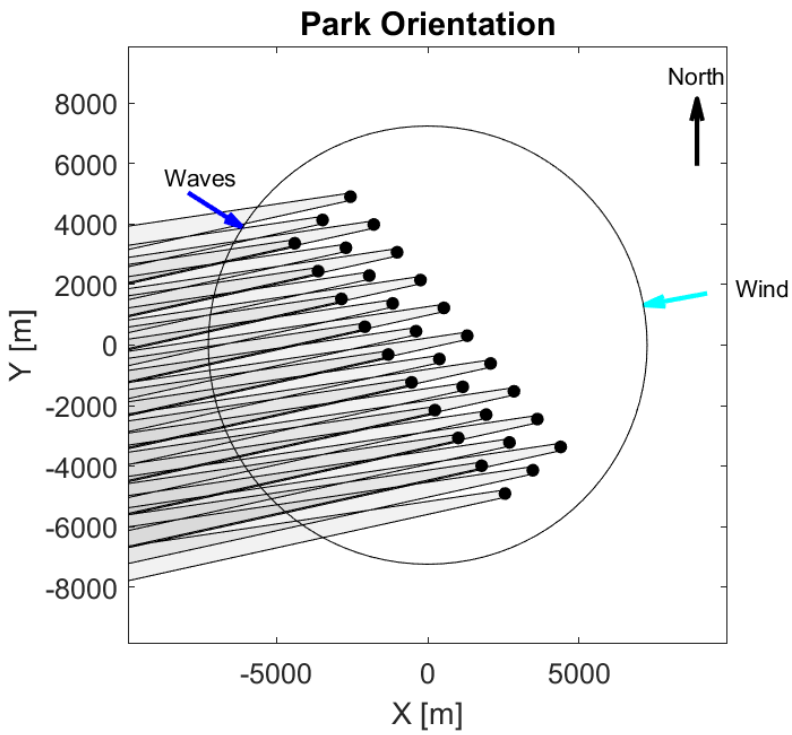

Figure 11. OWF turbines display and main wind and wave directions. Output from the first block of the model.

Regarding the cable layout, a 6-branch system was chosen with a substation located in the centre of the wind farm in order to optimise cable savings (see Figure 12). These connections are important as they affect the dependency among turbines. For the turbines connection with the substation that transports all the energy to a second onshore substation, array cables are installed to transfer from one turbine to another. Some of the faults included in the model also affect this array cables. This is important because when one of them fails, all the other turbines depending on it stop producing until the fault is repaired.

The dependency scheme tries to keep the most exposed turbines to meteorological factors at the end of the dependency chain, as they will be the ones that will fail the most:

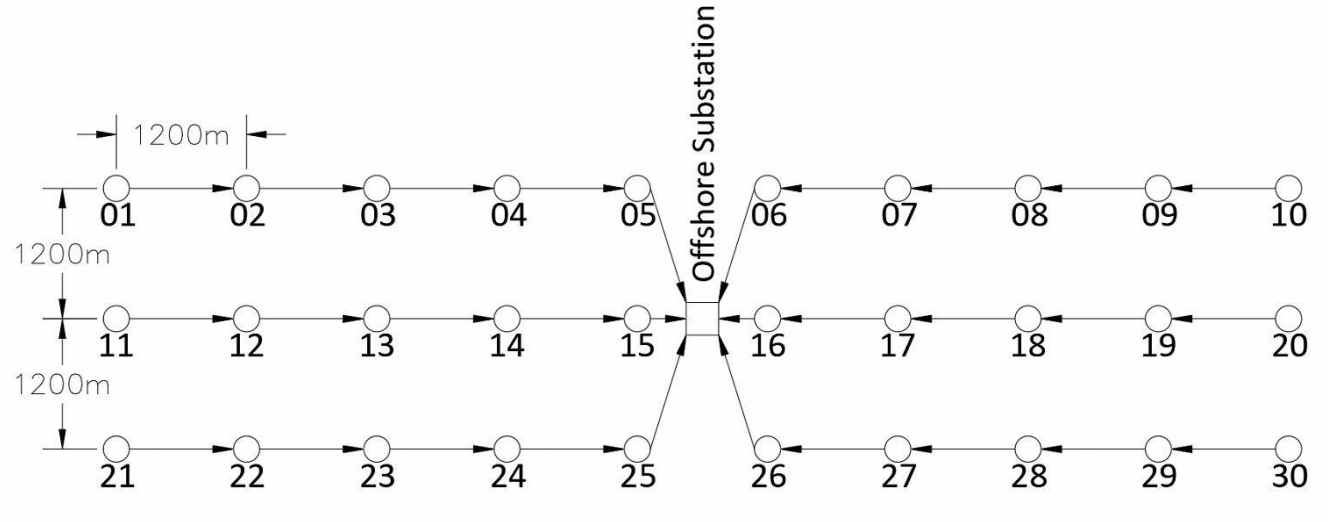

Figure 12. Offshore Wind Farm layout with array cables connections.

5.1.2 METOCEAN DATA

The metocean data have been obtained from the IH Cantabria database (IHDATA), specifically those corresponding to the site and O&M port coordinates.

Once the information has been collected, it is necessary to process the data to prepare them in the format required by the model. Using a pre-processing programme designed by the author, the records provided by IH Cantabria are analysed and the parameters necessary for the simulator are selected, at the same time the period extension of the records is chosen. This extension must coincide with the lifespan of the OWF, which for this project is 30 years (the usual value for this type of wind farms).

The data provided do not have wind speed values for the hub height, so the Hellmann exponential law has been used. This law correlates the wind speed measurements at two different heights:

$$V_i = V_0 * \left(\frac{z_i}{z_0}\right)^{\alpha}$$

Where:

- z_i is the desired height.
- V_i is the wind speed at the desired height.
- z_0 is the height which is referred the known wind speed measurement.
- V_0 is the known wind speed measurement.

- α is friction coefficient or Hellman exponent.

In this case, the wind database corresponds to the 10 m height sensor, the friction coefficient for Offshore Wind Farms is 0.14 and the desired height is 150 m, which corresponds to the hub height.

$$V_{hub} = V_{10} * \left(\frac{150}{10}\right)^{0.14}$$

At the end of this process, it is obtained a metocean file which contains information of waves (significant height, peak period, peak enhancement factor and directional spreading factor), wind (speed and direction at 10 m and hub height) and currents (speed and direction at the free surface).

5.1.3 O&M STRATEGY

As previously mentioned, the O&M port will be the San Cibrao port, 40 km from the chosen OWF location. This port in addition to the site coordinates are the two points forming the transit route taken by the vessels to perform the O&M activities.

5.1.3.1 HEAVY MAINTENANCE METHOD

Part of the inputs is the establishment of the steps that define heavy maintenance. This type of maintenance is the most complex and requires the transport of the damaged component to port for repair or replacement by a new one. This process is defined in a separate file to be able to indicate different constraints for the different steps according to their needs. The heavy maintenance considered is a tow-in process:

1. First, there will be a logistic time of 240 hours. This is the time from the detection of the heavy fault to the start of the second step. During this time a heavy vessel, which is not usually owned, is found available and the necessary spare parts are ordered to deal with the detected fault.
2. Once the logistic time has elapsed, the heavy vessel begins its trip from the port to the site at a speed of 20 km/h (unloaded speed). After arriving at the OWF, it will need 4 hours for positioning and disconnecting the turbine. Finally, the turbine is tow to port at a speed of 10 km/h (loaded speed).

3. At the port, 72 hours will be dedicated to carry out the necessary repairs. These 72 hours do not have to be consecutive, if the wind conditions do not allow it, the programme will pause the repair time and continue when the weather allows it.
4. Finally, the heavy vessel returns to the site towing the repaired turbine at a speed of 10 km/h (loaded speed). As in the second step, 4 hours are spent on positioning and connecting the turbine again. After the repair of the heavy fault, the vessel returns to port at a speed of 20 km/h (unloaded speed).

5.1.3.2 FAULT DEFINITION

In this section, the light fault Table 3 as well as the medium fault typologies Table 4 considered in this project are presented. Both the fault typology and its corresponding failure rate have been obtained from a 350 offshore wind turbines database [14,16] Although failure rate values can be found in other sources, they are not as detailed and generally use a combination of onshore and offshore registers, which is not applicable since offshore wind turbines have much higher failure rates [16, 17]

To ensure that the model is able to process the different types of failures, it is necessary to specify the following parameters for each of the types:

- **Constant**: In this field, it is specified whether to use a constant failure rate for the entire lifespan or to apply an annually discretised failure rate instead.
- **Time**: this shall include the duration of the on-site failure repair, without including transport and boatlanding.
- **Switchgear**: In this field it is specified yes or no depending on whether the type of fault affects the switchgear or not. If it does, all the turbines dependent on the damaged turbine will stop producing energy until the fault is repaired.
- **Lifting**: This column is only applicable for medium faults and determine if lifting is required for the fault reparation. If so, more restrictive wind speed constraint will be applied for workability computation.
- **Power Loss**: As explained above, not all faults affect production in the same way, as there are minor faults that do not interfere with the normal operation of the turbine. When a type of failure requires the total shutdown of the turbine, the percentage of loss will be

100 %, and in cases in which it can continue producing totally or partially, the percentage of power loss will be a value between 0 and 100, depending on the type of failure.

- **Failure Rate**: In this column, the failure rates obtained from the [14] research are shown.

In both, time and power loss columns of Table 3 and Table 4, the values have been established based on the knowledge generated in previous projects with which the research group of the offshore engineering department at IH Cantabria has collaborated.

Table 3. Light fault definition

Name	Constant	Time	Switchgear	Power Loss	Failure Rate
Pitch/Hyd	NO	6	NO	100	0,824
Other components	NO	4	NO	100	0,812
Generator (2-stage) PMG + FRC	NO	10	NO	100	0,485
Gearbox (2-stage) PMG + FRC	NO	10	NO	5	0,395
Blades	NO	12	NO	100	0,456
Grease/Oil/Cooling liq.	NO	4	NO	100	0,407
Electrical components	NO	4	NO	0	0,358
Contactor/Circuit Breaker/Relay	NO	6	YES	5	0,326
Controls	NO	3	NO	100	0,355
Safety	NO	4	NO	100	0,373
Sensors	NO	4	NO	50	0,247
Pumps/Motors	NO	6	NO	100	0,278
Hub	NO	6	NO	100	0,182
Heaters/Coolers	NO	4	NO	0	0,190
Yaw system	NO	10	NO	5	0,162
Tower	NO	16	NO	100	0,092
Power converter (2-stage) PMG + FRC	NO	6	NO	100	0,076
Service items	NO	8	NO	0	0,108
Transformer	NO	8	NO	0	0,052

Table 4. Medium fault definition

Name	Constant	Time	Switchgear	Lifting	Power Loss	Failure Rate
Pitch/Hyd	NO	24	NO	YES	100	0,179
Other components	NO	8	NO	NO	100	0,042
Generator (2-stage) PMG + FRC	NO	20	NO	YES	100	0,321
Gearbox (2-stage) PMG + FRC	NO	40	NO	YES	100	0,038
Blades	NO	40	NO	YES	100	0,010
Grease/Oil/Cooling liq.	NO	10	NO	NO	100	0,006
Electrical components	NO	16	NO	NO	100	0,016
Contactor/Circuit Breaker/Relay	NO	12	YES	NO	100	0,054
Controls	NO	8	NO	NO	100	0,054
Safety	NO	12	NO	NO	100	0,004
Sensors	NO	8	NO	NO	100	0,070
Pumps/Motors	NO	12	NO	NO	100	0,043
Hub	NO	10	NO	YES	100	0,038
Heaters/Coolers	NO	8	NO	NO	100	0,007
Yaw system	NO	24	NO	YES	100	0,006
Tower	NO	40	NO	NO	100	0,089
Power converter (2-stage) PMG + FRC	NO	12	NO	YES	100	0,081
Service items	NO	24	NO	NO	100	0,001
Transformer	NO	12	NO	YES	100	0,003

The heavy maintenance in this model combines all the failure rates referring to this category and combine them having just one Heavy faults failure rate equals to 0.265 according with the same source used for the light and medium categories [14]. The heavy maintenance method explained in the previous section in the applicable when one heavy fault occurs.

For heavy faults is considered:

- The repair time is 72 hours (at San Cibrao port).
- This type of fault affects the switchgear.
- There is a hundred percent of power loss.
- The failure rate is constant.

5.1.3.3 VESSEL CHARACTERISTICS

There are several different types of vessel contracts, which mainly differ in the degree of availability offered. For this project it is considered that the medium vessels are on property, which means the vessels are available whenever these are required.

The vessel chosen as medium O&M vessel is the CTV-30 (30 metres in length). The characteristics of this type of vessel are the following (see Table 5):

Table 5. CTV-30 characteristics.

Medium CTV Data	
Static friction coefficient bumper-fender:	0,6
Thrust force of the vessel against the platform (N):	300000,0
CTV speed (knots):	26,0
CTV limiting Hs (m):	2,5
CTV-platform hydrodynamic database:	CTV30_TRLPLUS_hydrobase.mat
CTV limiting wind speed (m/s):	25,0

The constraints used for O&M activities are defined below for the light and medium fault categories. They are applied for the workability and accessibility calculation.

- **Light faults reparation characterization:**

Table 6. O&M constraints for light faults.

Crew transfer limits data:	
Relative Roll rotation operational limits (deg):	2,5
Relative Pitch rotation operational limits (deg):	10,0
Relative Yaw rotation operational limits (deg):	2,5
Minimum jumping window size (s):	10,0
Proportion of time for which the jump must be possible:	0,33
Maximum Hs allowed (m):	2,5
Workability limits data:	
Maximum vertical acceleration allowed RMS (g):	0,2
Maximum horizontal acceleration allowed RMS (g):	0,1
Maximum tilt allowed RMS (deg):	6,0

Maximum wind speed at hub [WITHOUT LIFTING](m/s):	8,0
Weather windows limitations:	
Logistic time (h):	4,0
Minimum working time (h):	2,0
Maximum working time (h):	24,0
Work limited to day light:	YES
Transport limited to day light:	NO

- **Medium faults reparation characterization:**

Table 7. O&M constraints for medium faults.

Crew transfer limits data:	
Relative Roll rotation operational limits (deg):	2,5
Relative Pitch rotation operational limits (deg):	10,0
Relative Yaw rotation operational limits (deg):	2,5
Minimum jumping window size (s):	10,0
Proportion of time for which the jump must be possible:	0,33
Maximum Hs allowed (m):	2,5
Workability limits data:	
Maximum vertical acceleration allowed RMS (g):	0,15
Maximum horizontal acceleration allowed RMS (g):	0,07
Maximum tilt allowed RMS (deg):	4,0
Maximum wind speed at hub [WITHOUT LIFTING](m/s):	8,0
Maximum wind speed at hub [WITH LIFTING] (m/s):	4,0
Weather windows limitations:	
Logistic time (h):	4,0
Minimum working time (h):	2,0
Maximum working time (h):	24,0
Work limited to day light:	YES
Transport limited to day light:	NO

In order to understand what the limiting wave height will be, an additional hydrodynamic analysis has been carried out and the accessibility rose shown in Figure 13 has been extracted.

This figure shows the limiting wave height for several combinations of wave heading and wave peak period. The methodology described in section 3.2 is applied to each combination, increasing the wave significant height until finding the limiting factor. The peak enhancement factor and the directional spreading factor are constant among all combinations, since this figure is only used to gain an idea of the magnitude of the limiting wave height and its dependency with wave heading and period

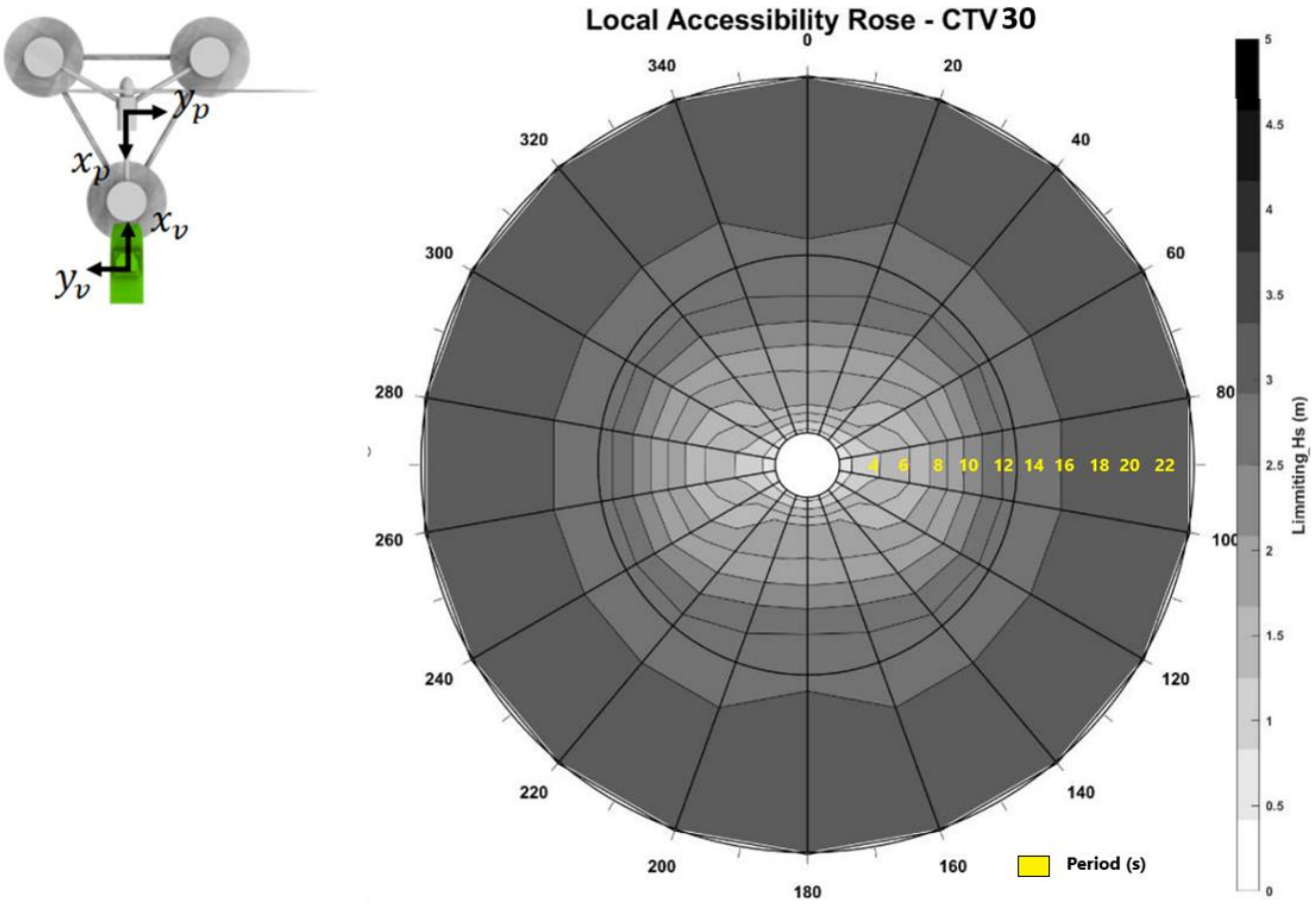

Figure 13. Limiting regular wave height for OC4-CTV30 system.

The constraints deduced from the accessibility rose and the limits established at the beginning of this section are compatible among them. The model takes both of them into account when determining the accessibility in the second module of the simulator: Light and medium repairs weather windows.

5.1.4 BASE CASE RESULTS

With the base case inputs explained in the previous sections, the model is run for constant failure rates. It has been defined those 40 simulations will be performed.

The number of simulations for each scenario is important because the random distribution of the faults over the lifespan could cause the data to coincide at points in the time series that are meteorologically very favourable or unfavourable for O&M, giving a biased reading of reality. In order to solve this problem, it is necessary that the number of simulations is high enough so that if one of these extreme cases occurs, when taking the average of all the simulated cases, its impact on the results is mitigated. On the other hand, it is not advisable for the number of simulations to be excessively high, as this would mean a longer execution time per scenario and would slow down the process of obtaining results enormously.

All the outputs corresponding to the base case provided by the model are presented below.

5.1.4.1 WIND POWER PRODUCTION

In this first module, the simulator calculates the ideal energy production that the OWF would be able to generate if there were no faults, only taking into account the meteocean conditions. Figure 14 and Figure 15 show the wave and wind roses on site. We can see how waves come mainly from the northwest, which implies that due to the location of the wind farm, turbines 1, 11 and 21 will be the hardest hit (see Figure 11 and Figure 12). This is the reason why, when designing the array cables, these turbines are placed at the end of the dependency chain, so that no other turbines will be affected in the case of a switchgear failure.

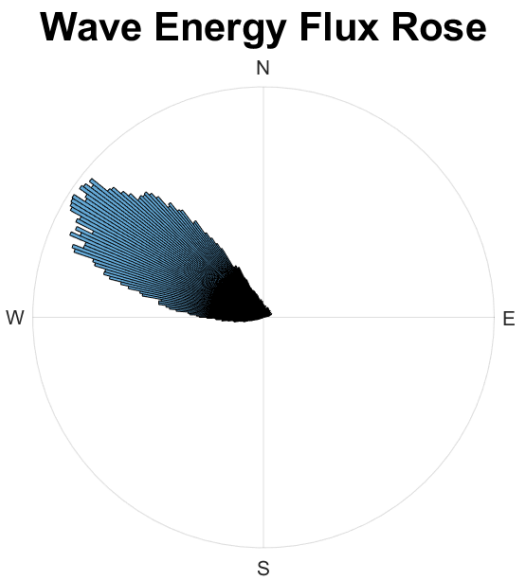

Figure 14. Wave energy flux on site (normalized).

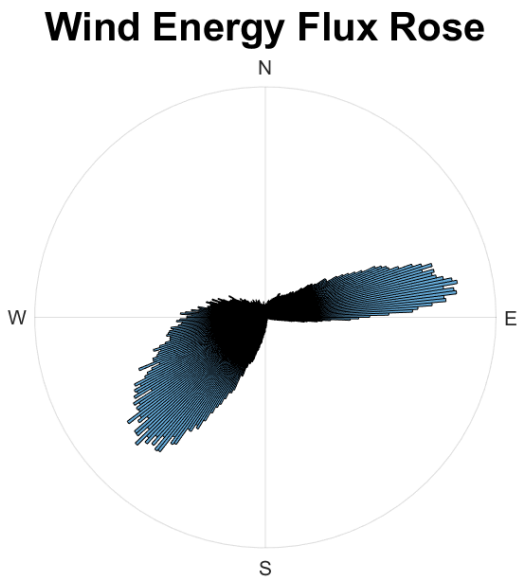

Figure 15. Wind energy flux on site (normalized).

On the other hand, the model also extracts Figure 11 about the layout of the wind farm as well as all the turbine wakes and main wind and wave directions.

In the following graph (Figure 16), it can be seen how the energy production varies annually. The energy production at any given time is obtained from the power curve (Figure 10) associated to the turbines as long as the significant wave height is lower than the operational limit (8.5 m) and the wind speed is between cut-in and cut-out (3 m/s and 25 m/s).

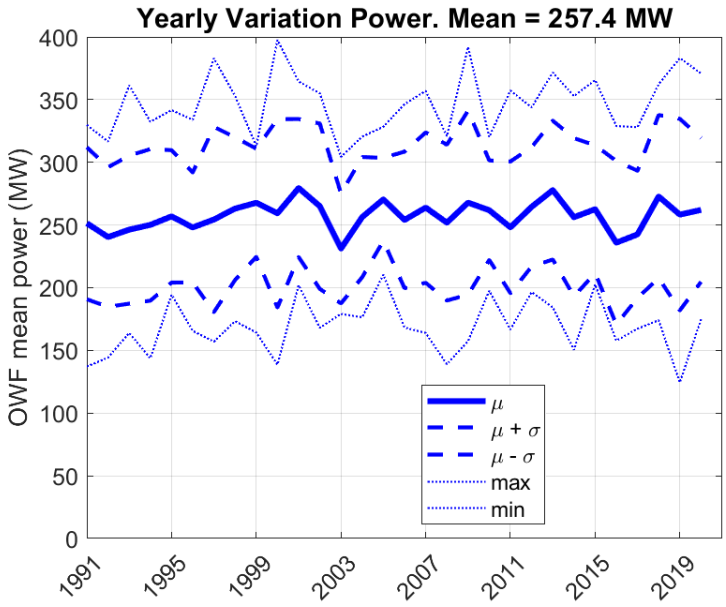

Figure 16. Inter-annual variation analysis of potential energy production.

In the following figure, Figure 17, it is observed how the potential energy production decreases from May to September due to the lower wind speeds and during the rest of the year the wind speed is higher so that the production as well.

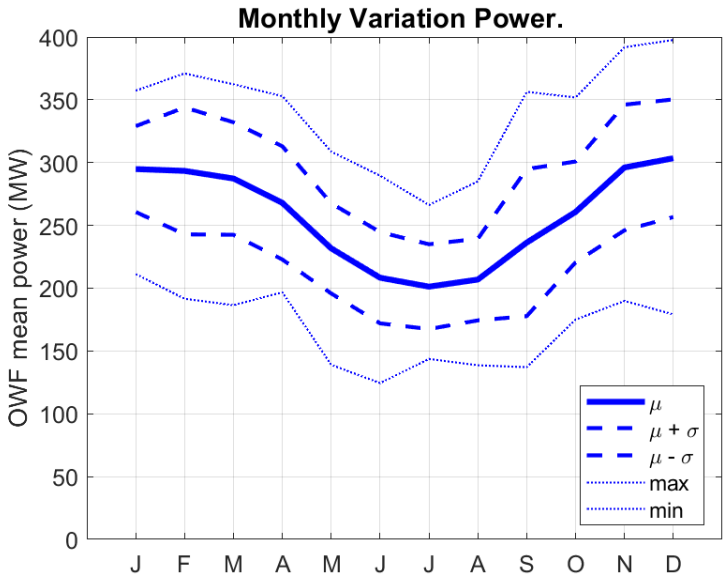

Figure 17. Intra-annual variation analysis of potential energy production.

5.1.4.2 LIGHT AND MEDIUM REPAIRS WEATHER WINDOWS

Based on these inputs, the intra-annual and inter-annual variation analyses are performed for three different parameters:

- **Transportability**: percentage of time that it is possible to go to site and come back with respect to the time that it would be possible if the metocean conditions were ideal. A 100% means that there is no impact of metocean conditions over transportability, lower rates means that there will be influence of the ocean conditions over this parameter.
- **Workability**: percentage of time that it is possible to work at the site, mounted on a wind turbine, with respect to the time that it would be possible if the metocean conditions were ideal. It does not consider the effect of transport or minimum working time. A 100% means that there is no impact of metocean conditions over workability, lower rates means that there will be influence of the ocean conditions over this parameter.
- **Accessibility**: it combines transportability, workability and working time. A 100% means that there is no impact of metocean conditions over accessibility, lower rates means that there will be influence of the ocean conditions over this parameter. The accessibility shows the percentage of the year when it is possible to carry out the O&M activities.

This analysis is performed for medium CTV and both fail types, and the results are shown in figures between Figure 18 and Figure 23.

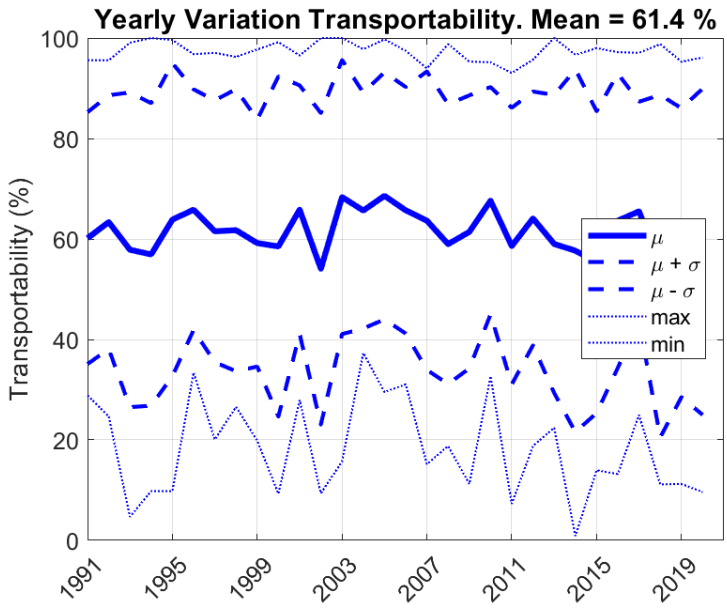

Figure 18. Inter-annual transportability.

In the case of workability, the conditions are much more restrictive than for transportability so that the percentage of average time per year possible is much lower (29.5 %).

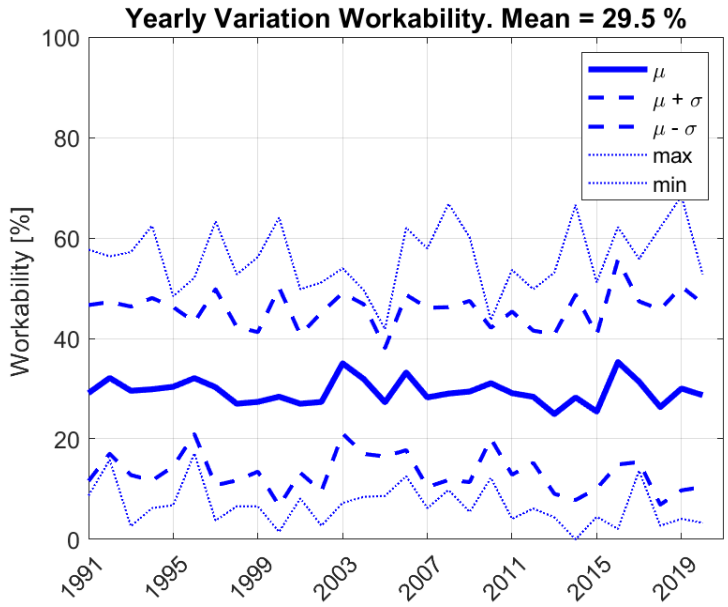

Figure 19. Inter-annual workability. Light and Medium faults without lifting.

The same analysis is also carried out for those medium faults that require lifting for reparation, as the maximum wind speed allowed is 50 % lower than in the case of no lifting (4 m/s). This means that there are fewer hours per year that comply with the wind limitation and the workability is significantly reduced.

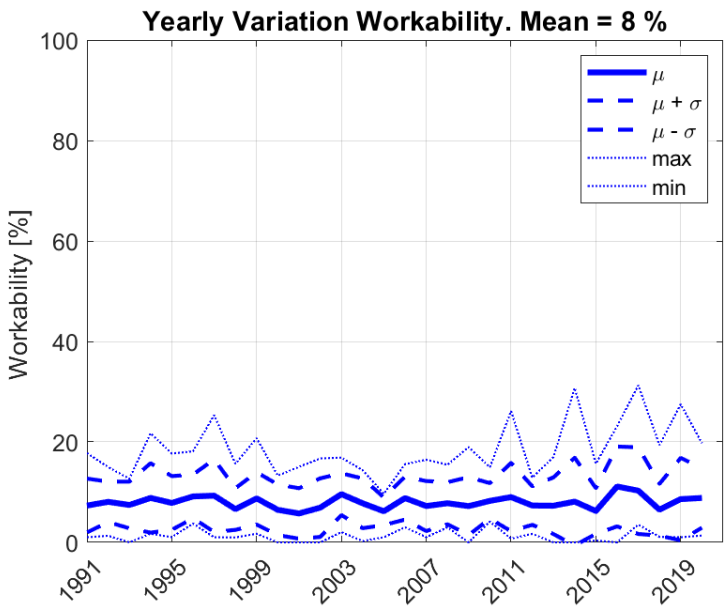

Figure 20. Inter-annual workability. Medium faults with lifting.

In order to access from CTV to the floating platform, it is necessary to find timeperiods longer than the minimum working time (4 hours) in which both transport and workability are permitted. For this purpose, the 61.4 % of the time in which transport can be carried out is combined with the 29.5 % of the time in which offshore work can be performed. From this comparison the timeperiods longer than 4 hours are selected, from which it is derived that only an average of 23.6 % of the time per year O&M can be undertaken.

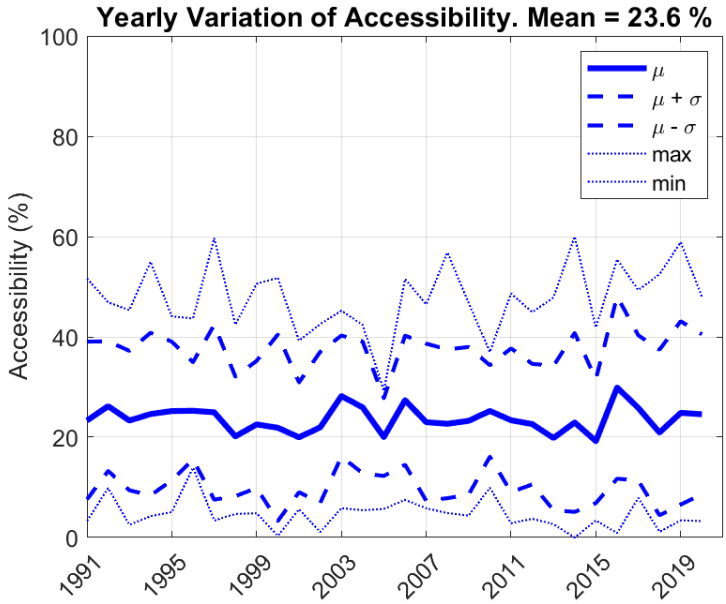

Figure 21. Inter-annual accessibility. Light and Medium faults without lifting.

Predictably, as workability is reduced for the medium faults with lifting, the same is found to be true for the accessibility of these types of faults.

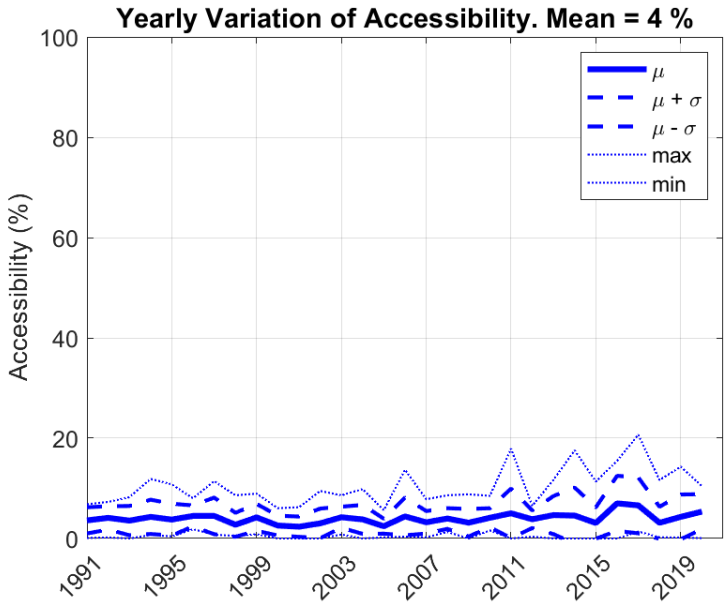

Figure 22. Inter-annual accessibility. Medium faults with lifting.

Logically, as can be seen in the figure below, accessibility increases significantly in the summer months as the weather conditions become milder. This occurs because both transportability and workability increase in this season as they have the same intra-annual trend as accessibility.

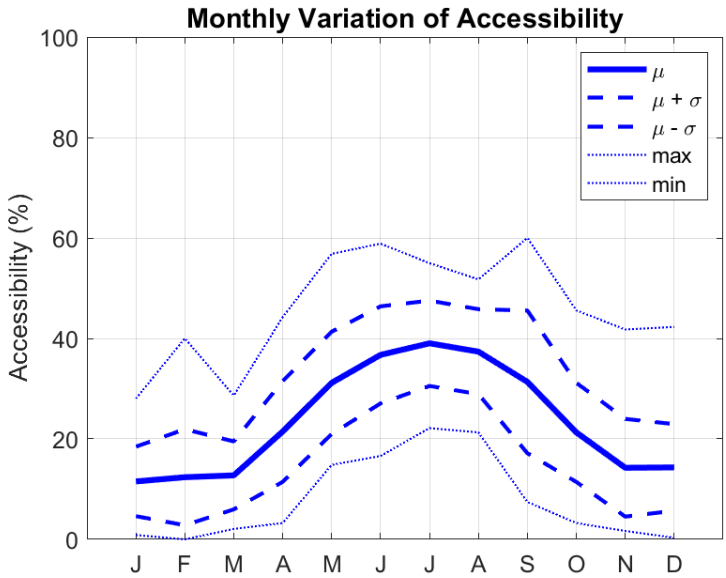

Figure 23. Intra-annual accessibility. Light and Medium faults without lifting.

5.1.4.3 HEAVY REPAIRS WEATHER WINDOWS

With the inputs presented in the section 5.1.3.1, the model computes and shows the inter-annual and intra-annual of the heavy repair time, shown in Figure 24 and Figure 25. The repair time is defined as the time that it would take to completely fix a heavy fault from the moment is produced, and the downtime is the time that the operations would be waiting for weather (the heavy repair time minus the ideal repair time).

The ideal Heavy maintenance activities takes 14 days, however the average repair takes around 31 days. Moreover, the standby period is also an important parameter, it is also important to notice that mean stand by period for a heavy maintenance is 17 days.

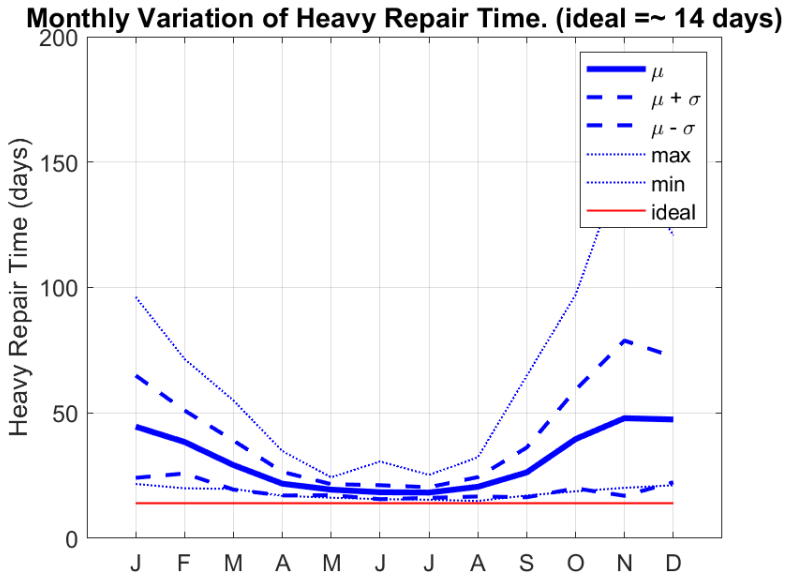

Figure 24. Intra-annual Heavy Repair time.

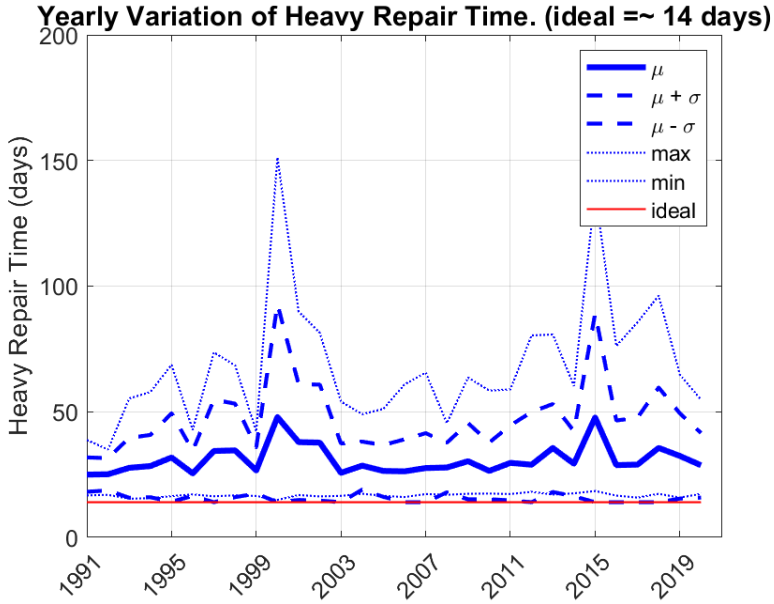

Figure 25. Inter-annual Heavy Repair time.

5.1.4.4 RANDOM FAULTS GENERATION

Module 4 is where the faults are generated and randomly assigned to the turbines. As output of the model, a set of tables are extracted, one for each simulation performed (40 in total), with all the faults generated, the repair time and the turbine assigned.

5.1.4.5 REPARATION ALGORITHM

The output sections explained above are applicable to all the scenarios shown throughout the project. In order to provide an explanation of consistent results, we will begin by showing and explaining the data corresponding to having five O&M vessels, as this will be the optimum fleet size to be obtained later in the analysis see Section 5.2.1.1 Optimization of the number of O&M vessels.

The reparation algorithm module uses outputs from all previously described modules as inputs, together with some of the inputs previously described, such as the logistic times. The results obtained are presented from Figure 26 to Figure 39.

- **Time availability**:

The model removes all wind-out-of-limits time from the calculation, i.e., low and high wind periods, in order to approximate a loss factor in the calculation of energy production. This indicator correlates the time when the turbine is producing with the time with the time when the turbine could be producing because the metocean conditions allow it.

$$Time\ availability\ [\%] = \frac{Number\ of\ hours\ generating\ kW}{Nº\ of\ hours\ that\ the\ wind\ is\ between\ cut-in\ and\ cut-out} * 100\ \%$$

This parameter shows the percentage of time that the turbine is not producing due to O&M activities. In Figure 26 it is possible to observe how time availability varies throughout the year, as expected, time availability in the summer season is significantly higher than in the winter. This is because the metocean conditions during winter are worse and it is needed to wait for a 4-hour weather window to start the maintenance, which occurs less frequently than in summer.

The Figure 27 shows the time availability variation along lifespan. The mean annual time availability computed is of 82%.

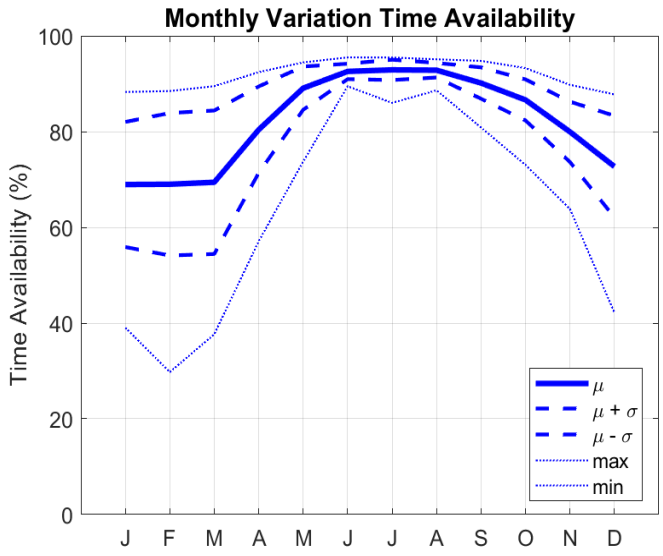

Figure 26. Intra-annual time availability.

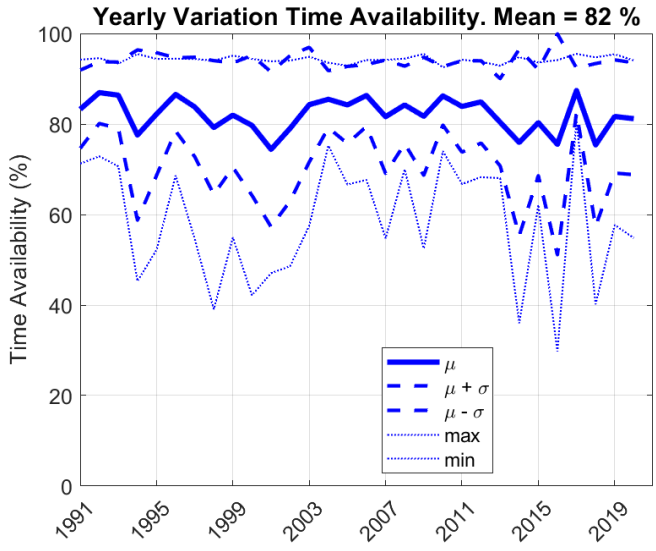

Figure 27. Inter-annual time availability.

- **Power availability**:

It is a similar concept to time availability and usually both indicators are in the same order of magnitude. The model accounts for all the kWh actually produced (considering faults) along the lifespan and divide it by the number of hours in that lifespan then take the outputs from the first module and calculate the kWh ideally generated and divide it by the number of hours in that lifespan. The power availability is the correlation between these two parameters.

$$Power\ availability\ [\%] = \frac{Mean\ power\ actually\ generated\ (in\ kW)}{Mean\ power\ potentially\ expected\ (in\ kW)} * 100\ \%$$

This indicator shows the percentage of power that the turbine is not producing due to O&M activities. In Figure 28 it is possible to observe how power availability varies throughout the year, as in the case of time availability, power availability in the summer season is significantly higher than in the winter. This is because the metocean conditions during winter are worse and it is needed to wait for a 4-hour weather window to start the maintenance, which occurs less frequently than in summer.

The Figure 29 shows the power availability variation along lifespan. The mean annual time availability computed is of 81.2%.

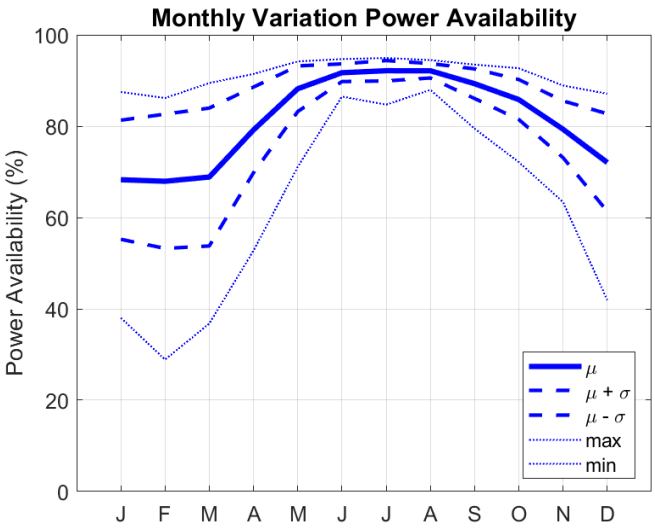

Figure 28. Intra-annual power availability.

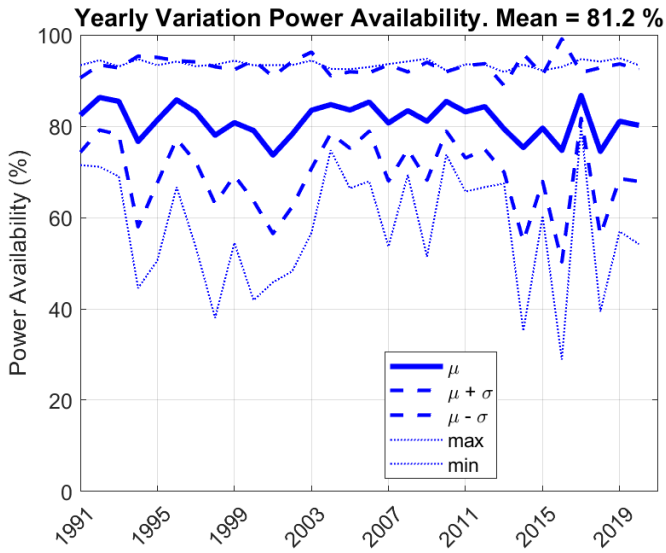

Figure 29. Inter-annual power availability.

- **Power production**:

It is the product of the mean power potentially expected extracted from the Energy production module and the power availability. It represents the mean power production for all the lifespan.

$$Power\ production\ [kW] = Mean\ power\ potentially\ expected\ (in\ kW) * Power\ availability$$

In both, Figure 30 and Figure 31, there is not much variability although the intra-annual shows a higher production in the winter months due to the greater resource availability. The inter-annual average is 204.6 MW, with fluctuations between 180MW and 220 MW.

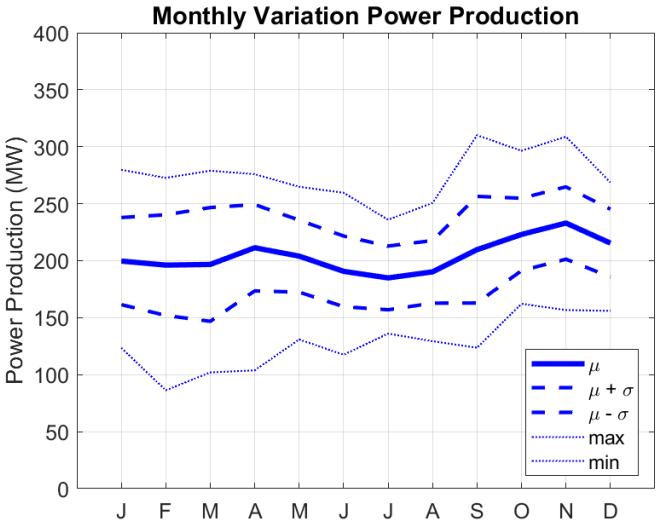

Figure 30. Intra-annual power production.

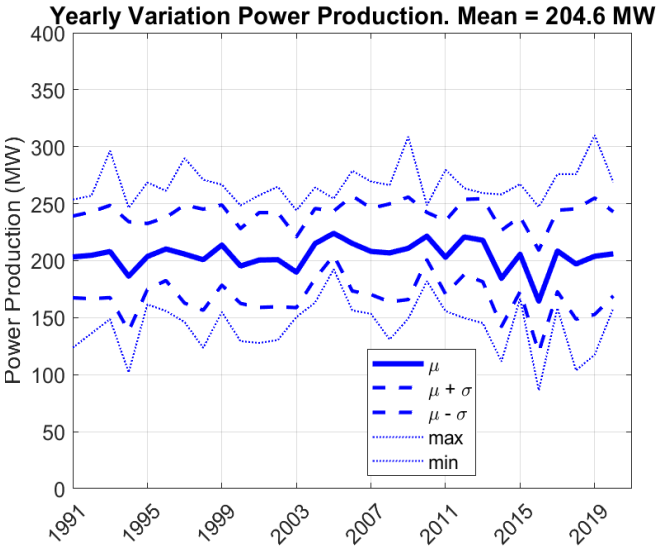

Figure 31. Inter-annual power production.

- **Total downtime**:

It is the ratio between the real time consumed from the fault detection until it is fully repaired, with the corresponding time spent waiting for a weather window, and the ideal repair time in the case of no metocean constraints. It represents the mean time needed to repair one fault and give us an idea about when the amount of cumulative faults is increasing. This second idea could be because of two reasons, in first place we could think that the metocean conditions are more severe and we are not able to proceed to the repair but it could be as well because there is not enough number of vessels to assist all the faults.

$$Downtime\ [\%] = \frac{Real\ repair\ time\ from\ fault\ detection\ until\ solved\ (h)}{Ideal\ repair\ time\ wothout\ metocean\ constraints\ (h)} * 100$$

From Figure 32 to Figure 37 the intra-annual and inter-annual three types of downtime computed by the model are shown. For the intra-annual figures (the ones on the left), it is easy to observe the huge seasonality between the fall semester, with more than 40 times the ideal total repair time, and the rest of the year with less than 10 times. For the inter-annual figures (on the right) down time is a bit higher for the medium faults but as an average the total weather downtime is the 1982.7%.

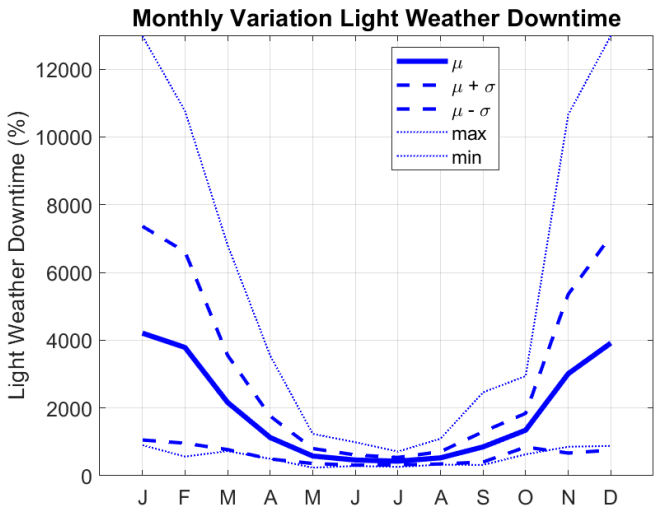

Figure 32. Intra-annual light faults downtime.

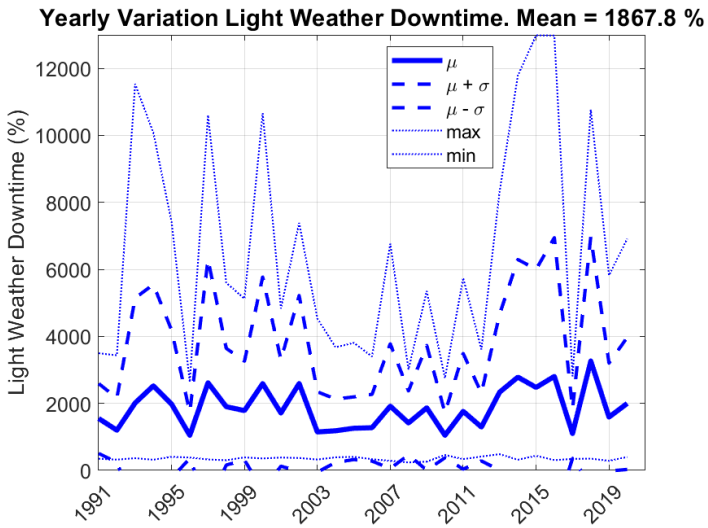

Figure 33. Inter-annual light faults downtime.

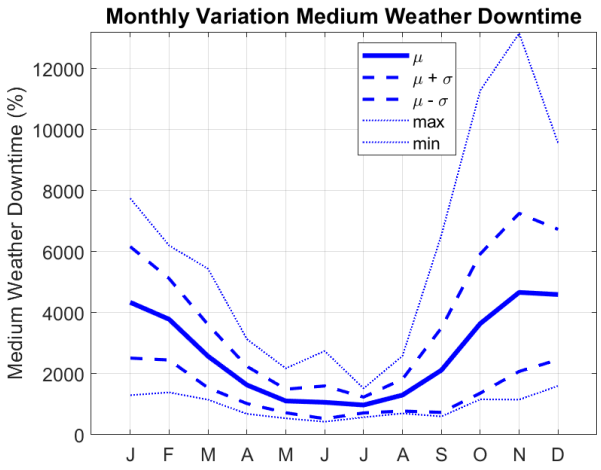

Figure 34. Intra-annual medium faults downtime.

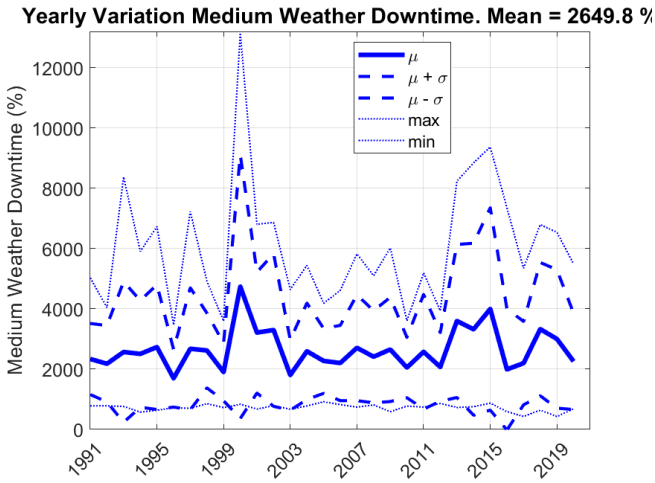

Figure 35. Inter-annual medium faults downtime.

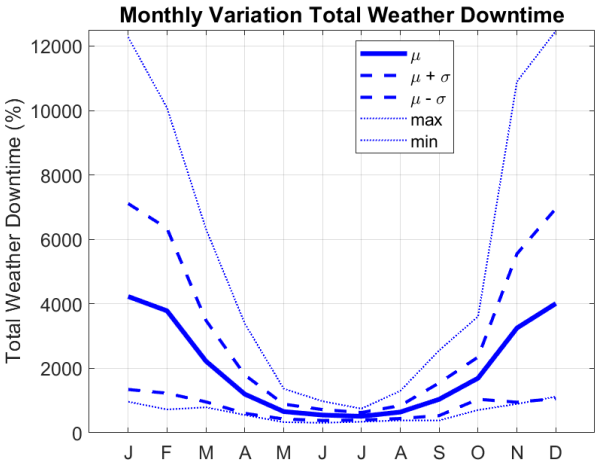

Figure 36. Intra-annual light and medium faults downtime.

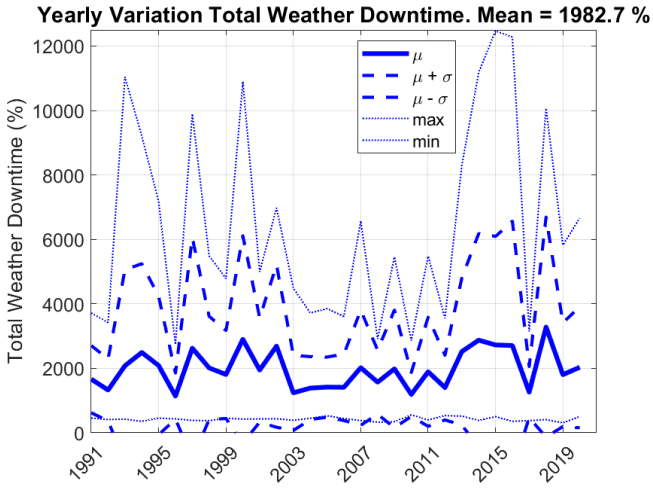

Figure 37. Inter-annual light and medium faults downtime.

- **CTV Trips**:

This parameter accounts for all the trips made by the medium vessel during repairs. Each repair (transport from port to site and back) counts as two trips. In an ideal case, the number of trips will be double the number of faults but depending on the size of the weather window, more than two trips may be needed to repair the same fault. In the case of small fleet sizes, the number of trips is very high because when a long weather window appears, until the repair of one fault is finished, the vessel cannot go to the next one, which wastes the weather window. For the same case with a large fleet size, it is possible to repair several faults at the same time.

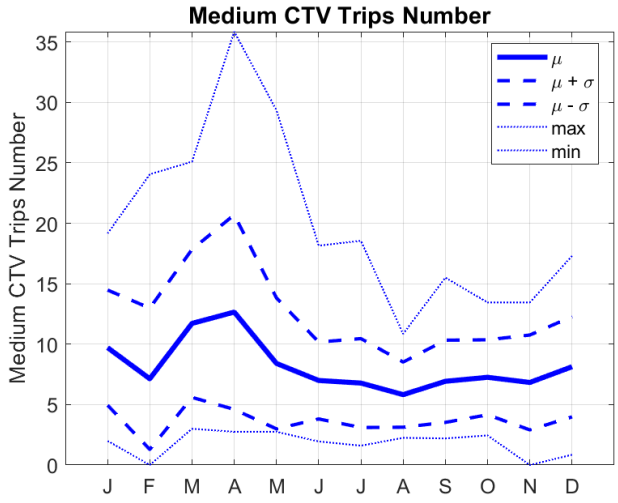

Figure 38. Intra-annual number of trips for medium CTV.

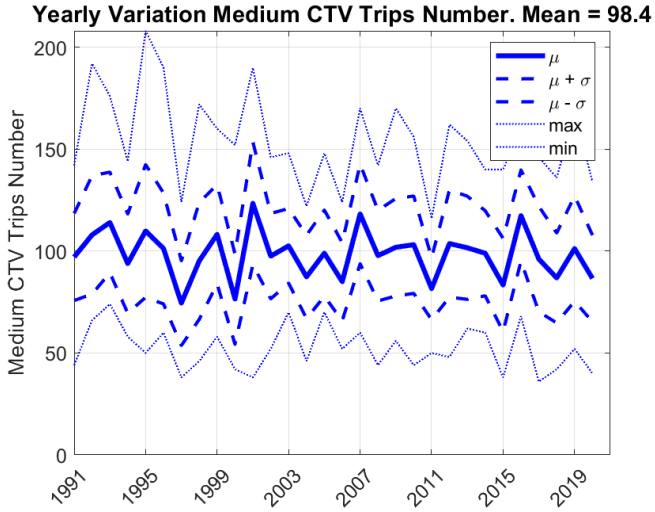

Figure 39. Inter-annual number of trips for medium CTV.

5.2 SENSIBILITY ANALYSIS

In this section, two sensitivity analyses will be developed. Firstly, the impact of the number of O&M vessels on the most representative indicators will be studied, and this will conclude with a techno-economic feasibility study in order to calculate the optimum fleet size.

Secondly, a sensitivity analysis will be carried out on different distributions of failure rates throughout the lifespan of the different turbine components and the results will be analysed with the purpose of knowing the impact of having a more detailed knowledge of the failure rates so that resources can be invested more efficiently in this area.

5.2.1 ON THE IMPORTANCE OF THE VESSEL NUMBER

For the sensitivity analysis on the fleet size, the number of vessels to be simulated has to be defined. In this project, it has been proposed to carry out an analysis with 10 scenarios that are essentially the same, but with only the number of vessels available for O&M activities being changed.

The analysis will consist of taking all the inputs already explained in the base case and changing the number of vessels from 1 to 10. The model is executed for all the scenarios and the independent outputs are obtained for each of them. This change in the fleet size only affects light and medium faults, as heavy faults are managed with only one vessel. The type of heavy vessels usually have a different contract and tend to be much smaller in number as there are fewer faults in this category.

Subsequently, a computer program has been generated to process the data and generate the figures that appear in the following analysis. This section will show the comparative results between the different simulated scenarios. Specifically, the analysis of time availability, power availability and total downtime will be shown. In all the graphs, the ten outputs of the corresponding parameter are compared in order to observe their evolution as the fleet size increases. As already mentioned in the output of the base case, the results corresponding to a single O&M vessel are not representative, since before half of the period for which the OWF is designed, it becomes inoperative due to a lack of capacity to deal with the reparation of the faults that accumulate.

- **Time Availability:**

In this figure, it is shown how the time availability increases as the fleet size increases. It can be seen how in the case of a single vessel, the time that the turbines are running decreases until after 10

years all the turbines stop running all the time of the year. In the rest of the cases, as the fleet increases, the time in which the turbines are not stopped due to failure also increases. When approximately 80 % time availability is reached, independently of the number of vessels, this value becomes stable. This is because the metocean conditions are exceeding the limits of accessibility and it is not possible to carry out repairs no matter how many vessels are hired. Table 8 shows the annual averages time availability for the different scenarios.

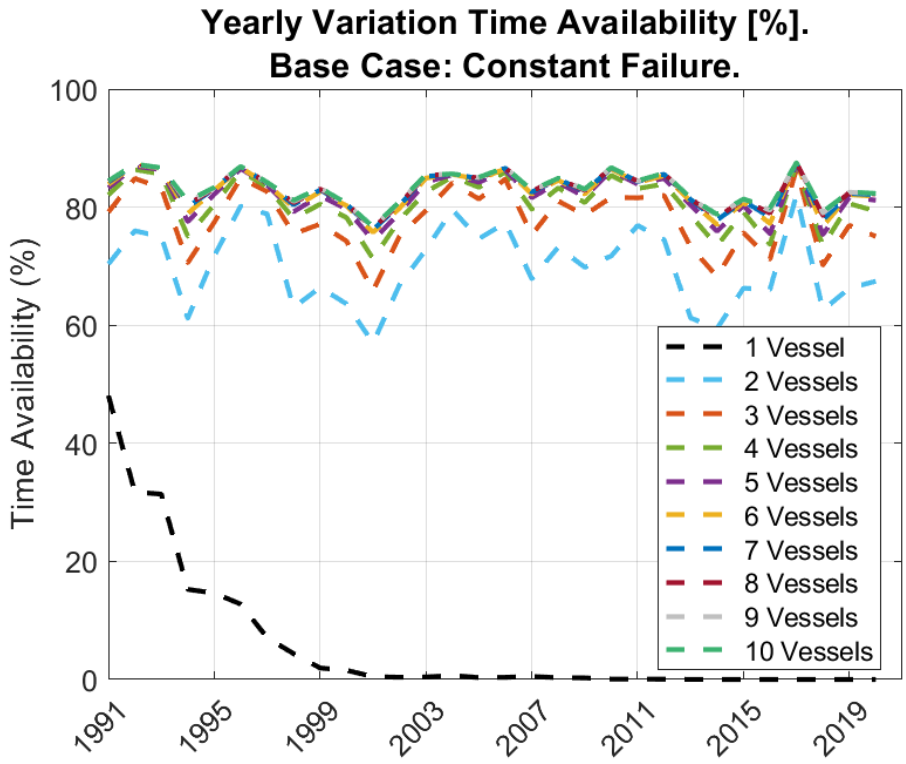

Figure 40. Comparison of inter-annual time availability for different fleet sizes.

Table 8. Mean annual time availability for different fleet sizes.

Number of O&M Vessels	Mean Annual Time Availability
1 Vessel	5.76 %
2 Vessels	69.99 %
3 Vessels	77.92 %
4 Vessels	80.79 %
5 Vessels	82.04 %
6 Vessels	82.64 %
7 Vessels	82.98 %
8 Vessels	83.15 %
9 Vessels	83.27 %
10 Vessels	83.35 %

- **Power Availability**:

Similar to the time availability case, an improvement is observed as the size of the fleet increases until reaching an upper limit of 82.5%. This limit represents the maximum usable production over the ideal production, since the other 17.5% is lost due to the time in which the turbine is stopped waiting to find a weather window longer than 4 hours in order to be repaired.

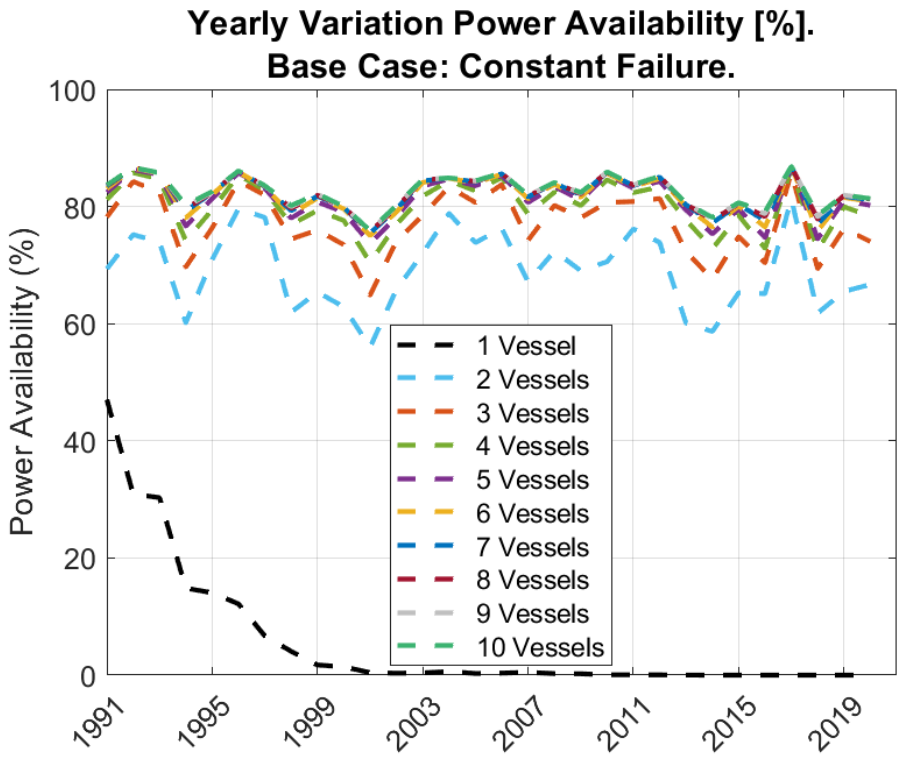

Figure 41. Comparison of inter-annual power availability for different fleet sizes.

Table 9. Mean annual power availability for different fleet sizes.

Number of O&M Vessels	Mean Annual Power Availability
1 Vessel	5.56 %
2 Vessels	69.13 %
3 Vessels	77.07 %
4 Vessels	79.98 %
5 Vessels	81.24 %
6 Vessels	81.85 %
7 Vessels	82.19 %
8 Vessels	83.37 %
9 Vessels	82.48 %
10 Vessels	82.56 %

- **Total Downtime**:

The first figure shows the total downtime for this case. It can be seen that with a single vessel it is not possible to carry out repairs because, as in Figure 40 and Figure 41 which showed the total stoppage of the OWF, in Figure 42 it can be seen how the downtime increases to 180000%. This means that a single failure with a 4-hour repair time would take almost a year to repair due to the lack of availability of vessels.

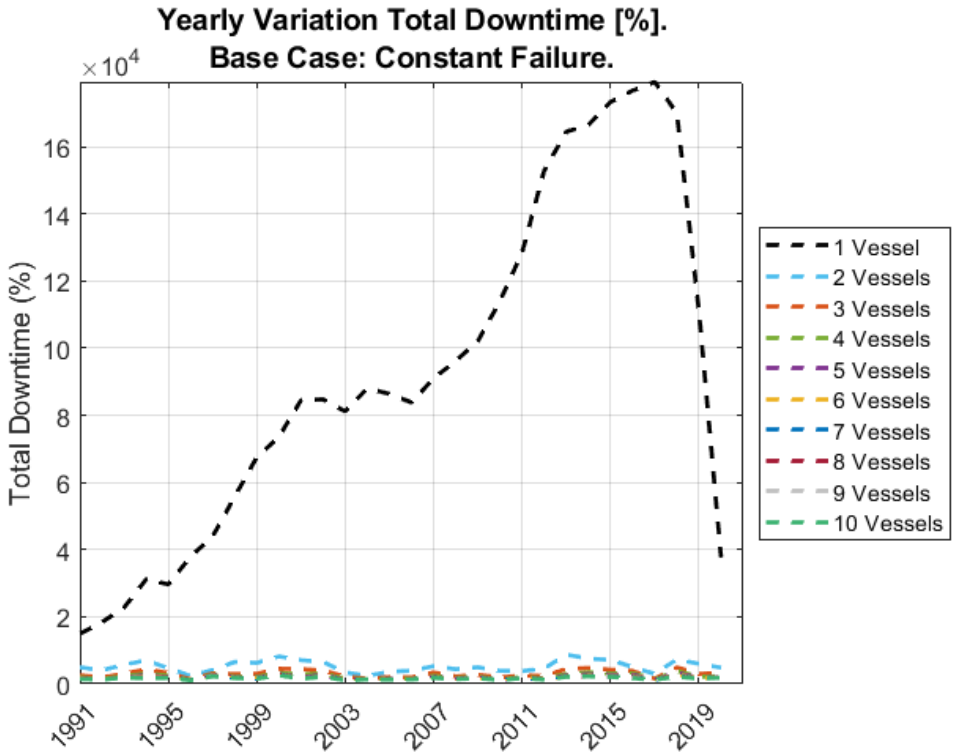

Figure 42. General view for comparison of inter-annual total downtime for different fleet sizes.

Figure 43 shows the same graph as above but excluding the results for a single vessel. It can be seen how the downtime reduces as vessels are added to reach a total downtime of 1650% where the downtime is irreducible due to the metocean conditions. This total downtime of 1650% means that on average the repair of any fault will require 16.5 times the ideal repair time.

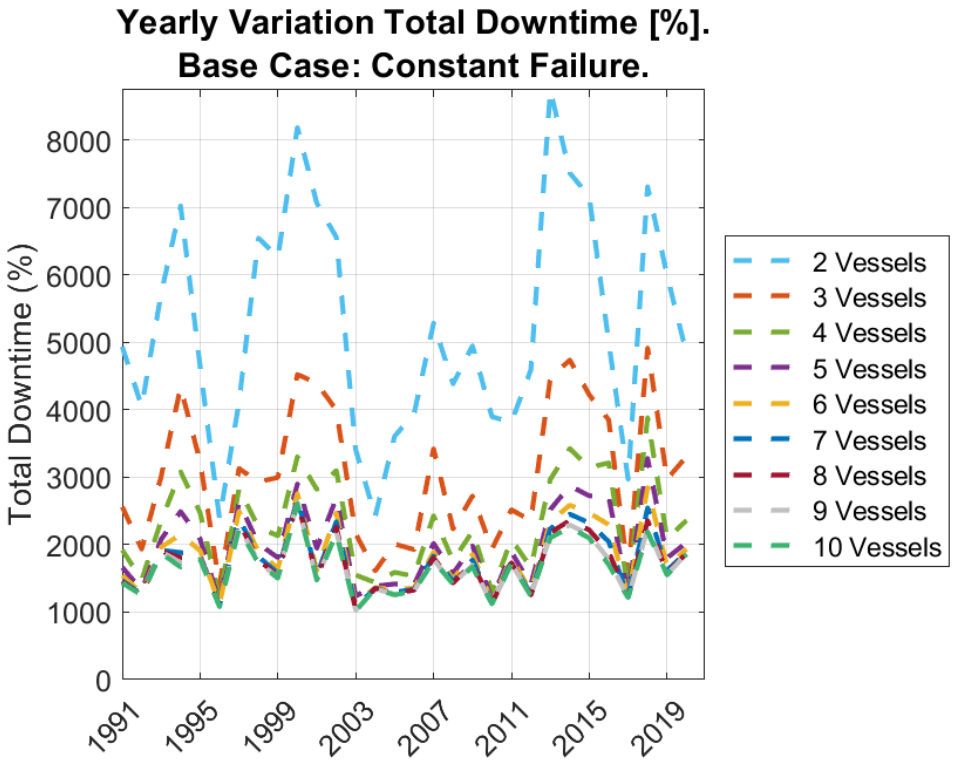

Figure 43. Comparison of inter-annual total downtime for different fleet sizes except 1 vessel.

Table 10. Mean annual total downtime for different fleet sizes.

Number of O&M Vessels	Mean Annual Total Downtime
1 Vessel	92252.16 %
2 Vessels	5243.13 %
3 Vessels	3046.42 %
4 Vessels	2296.96 %
5 Vessels	1982.69 %
6 Vessels	1830.48 %
7 Vessels	1748.39 %
8 Vessels	1704.21 %
9 Vessels	1674.82 %
10 Vessels	1654.36 %

5.2.1.1 OPTIMIZATION OF THE NUMBER OF O&M VESSELS

As can be seen, it is not feasible to carry out the O&M tasks with only one vessel, at least 2 will be necessary to start with a normal behaviour of the wind farm, otherwise, the production would cease due to the failure of all the turbines from the tenth year onwards.

In any case, two vessels are not enough to operate the park, as the power availability will be 69%, which guarantees the non-viability of the OWF.

Power availability is a very significant indicator as it shows the power that is being obtained compared to the power that could be obtained if there were no faults or downtime, calculated in the first block of the model, Energy production.

In the following, the increase in power availability generated by the increase in the number of vessels has been calculated.

Table 11. Annual increased power availability per extra vessel.

Number of O&M Vessels	Mean Annual Power Availability	Increased Power Availability
1 Vessel	5.56 %	-
2 Vessels	69.13 %	Infinite
3 Vessels	77.07 %	11.82 %
4 Vessels	79.98 %	3.89 %
5 Vessels	81.24 %	1.63 %
6 Vessels	81.85 %	0.77 %
7 Vessels	82.19 %	0.43 %
8 Vessels	83.37 %	0.22 %
9 Vessels	82.48 %	0.14 %
10 Vessels	82.56 %	0.10 %

- **The same analysis was carried out in economic terms**:

For this, the real annual average power production for each of the fleet sizes has been taken from the model outputs, which means that the time in which the turbine is not producing due to failure has already been discounted. The average price per MWh in Spain has also been obtained. And with this data, the annual profits have been calculated according to the size of the fleet:

$$Benefit = Mean\ Annual\ Power\ Production * Hours\ in\ a\ year * Energy\ Price$$

Average price of MWh in Spain (September 2021): 130 €/MWh [30]

$$Benefit = PP_{nv}\frac{MW}{year} * \left(24\frac{h}{day} * 365\frac{days}{year}\right) * 130\frac{€}{MWh}$$

The results obtained from the above analysis are shown in the next chart:

Table 12. Annual increased benefits per extra vessel.

Number of O&M Vessels	Mean Annual Real Power Production [MW]	Benefit [Million €]	Annual increased benefits per extra vessel [Million €]
1 Vessel	13.59	15.48	-
2 Vessels	171.18	194.94	179.46
3 Vessels	192.78	219.54	24.60
4 Vessels	200.95	228.85	9.31
5 Vessels	204.57	232.96	4.12
6 Vessels	206.30	234.93	1.97
7 Vessels	207.28	236.05	1.12
8 Vessels	207.79	236.63	0.58
9 Vessels	208.13	237.02	0.39
10 Vessels	208.36	237.28	0.26

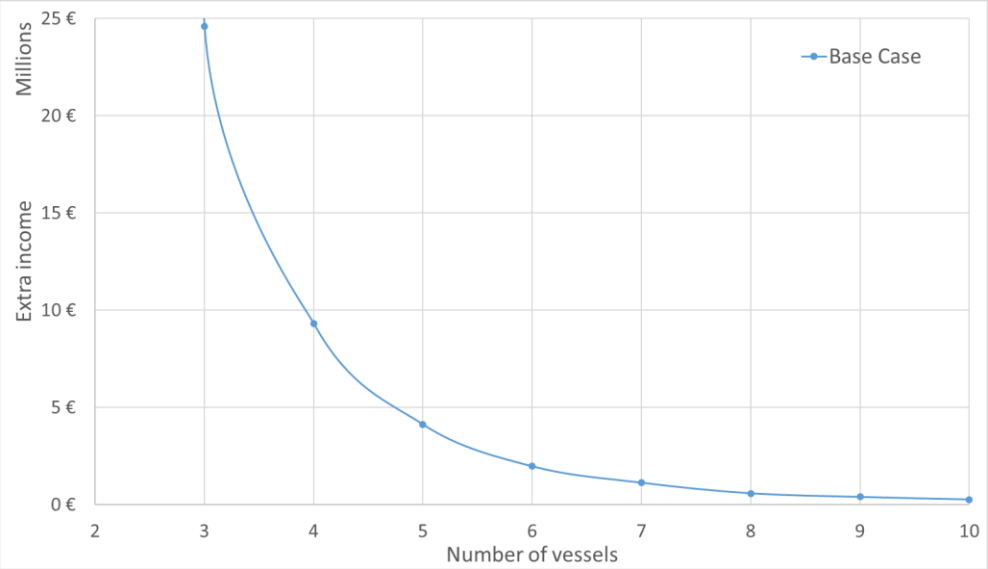

Figure 44. Variation on the increased benefits per extra vessel.

In Figure 44 it can be clearly seen how the increment in profits decrease as more vessels are added. In order to decide the most convenient number of vessels, this value must be compared with the extra cost of hiring a new vessel.

In this project it has been considered that 5 vessels is the optimal number of vessels to carry out the O&M tasks. 4 million euros extra as well as an improvement of more than 1 % of the power availability define the chosen option. In case the contract for a new vessel would cost more than 4 million euros, the fleet size would have to be set at four vessels or reduced until it becomes profitable.

5.2.2 IMPACT OF COMPONENT MATURITY OVER THE POWER PRODUCTION

In most studies concerning O&M simulation of offshore wind turbine components, constant failure rates for each turbine component[28] are being used. However, it has been shown that any component, whether in the wind industry or not, has a failure rate described by a bathtub curve.[14, 29] This curve requires a deeper knowledge of the individual components, which makes it difficult to apply in this field due to the relatively recent emergence of the wind industry and offshore platforms.

In some of the cases the database used for the research came in a huge percentage from onshore wind farm. Mixing offshore and onshore measurements it is positive for increasing the amount of data but it is not desirable because it has been exposed that failure rates of OWF are much higher than in the onshore wind sector. Something which might be expected taking into account the harder weather conditions [16, 17].

A bathtub curve is a lifetime distribution that is mainly used in industrial maintenance as it usually describes the deterioration mode of the different components. This type of curve is divided into 3 stages:

1. **Infant Mortality period = Youth stage**: It is a period of adjustment of the turbine components in which the failure rates are very high due to mistakes in production, assembly or commissioning that cause that during this first stage the failure rate starts being very high and goes down as the whole OWF is correctly adjusted.
2. **Normal operating period = Maturity stage**: This is the longest period of the three. During this stage the failure rate remains constant.
3. **Component degradation and fatigue = Wear-out stage**: because of the cumulative hours operating, the components generate an increase in the failure rate due to wear and tear.

It is not necessary that the first and third stages have the same slope but, in this project, as in many others, a symmetrical bathtub curve will be considered as no data is available for the third stage of the curve.

In order to calculate the corresponding curve, the failure rates provided by the publication used for this topic [14] have been added and therefore the failure rate of the whole turbine instead of per component for the first 8 years. Figure 45 shows these values for the whole turbine (without discretising

by components) for both LM and MM as well as for the sum of the two. The decay ratio between the start point and the end point of stage 1 is taken.

To avoid complexity and having many different bathtub curves, a common representative parameter for the whole turbine has been taken for light and medium faults (MM+LM).

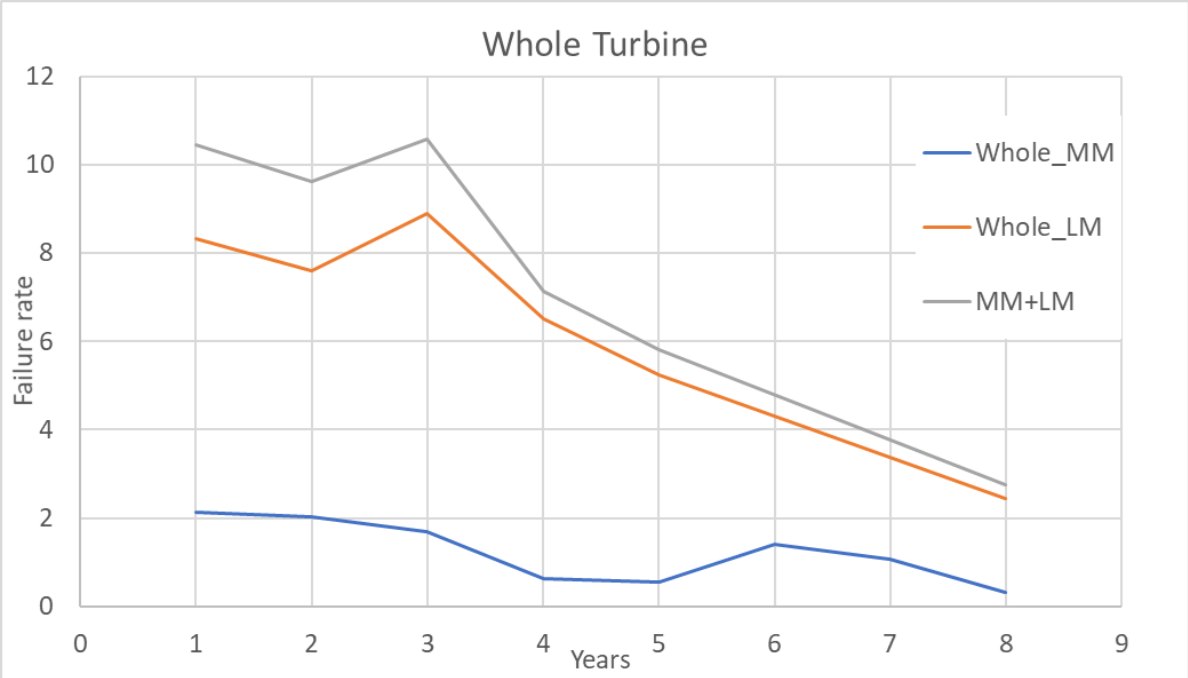

Figure 45. Data applied to obtain the bathtub curve slope. Data source: [14].

First of all a separate code has been created to generate the bathtubs where the inputs are the lifespan, the ratio between the highest and lowest point of the first stage and the duration of the youth stage.

Lifespan = 30 years.

The sensitivity analysis in this section consists of testing different types of bathtub curves for various durations of the first stage, in particular 5 types corresponding to 2, 4, 6, 8 and 10 years until maturity. The ratio between the high and low failure rate are obtained dividing the failure rate of the first year over the eighth year.

For the decay ratio calculation:

Table 13. Failure rates for the whole turbine.

	Year 1	Year 8
Light Maintenance (LM)	8.33	2.45
Medium Maintenance (MM)	2.13	0.31
Light and Medium Maintenance (LM+MM)	10.46	2.76

$$LM_{ratio} = \frac{8.33}{2.45} = 3.40 \ ; \quad MM_{ratio} = \frac{2.13}{0.31} = 6.87 \ ; \quad (LM + MM)_{ratio} = \frac{10.46}{2.76} = 3.79$$

According to what it was said stablished before about minimizing complexity so a common ratio was used for both fault categories (LM + MM = 3.79).

Once all the data needed is known a normalized bathtub curve per scenario (see Figure 46):

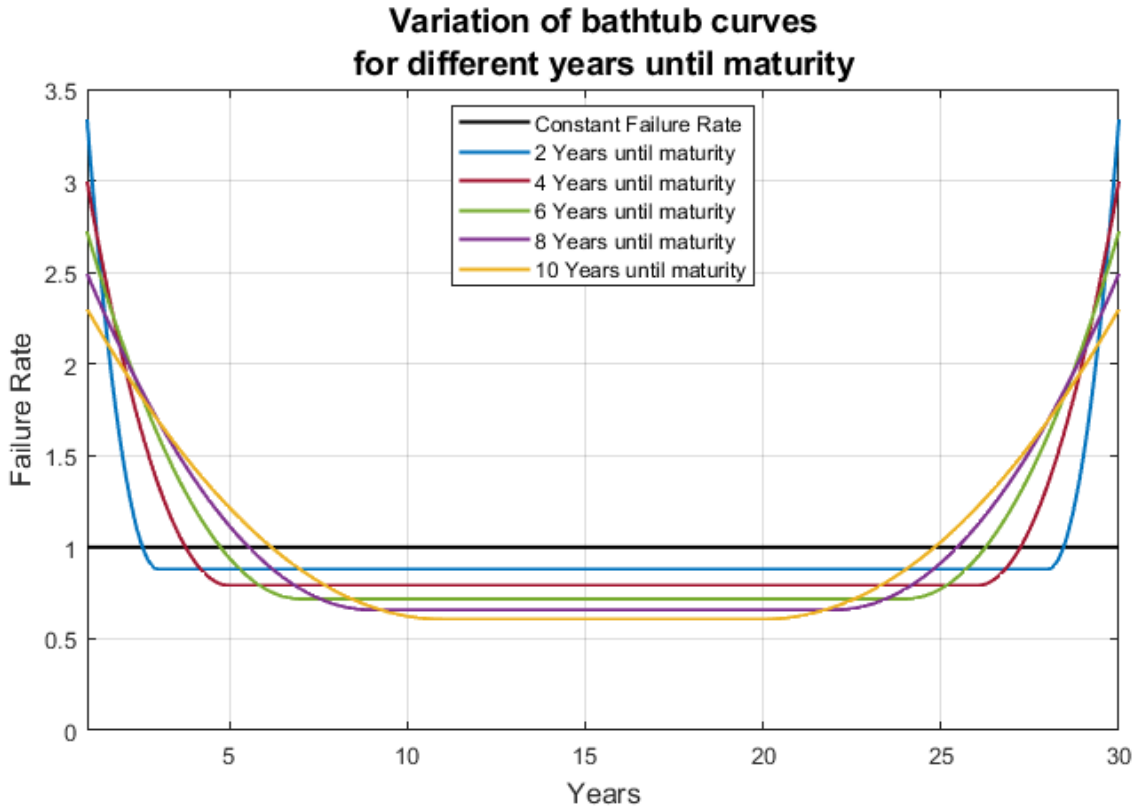

Figure 46. Different normalized bathtub curves to be used in the analysis.

After generating the normalized bathtub curve for each scenario (it is called normalized because the area under the curve is equal to 1) multiplying by the failure rate associated to each fault typology is needed. The aim of this calculation is to keep the number of faults throughout lifespan constant in every scenario of the project so the comparison is always made for the same number of faults.

As this research focuses on the logistic design considering that the failure rates and the number of vessels are variable for the medium and light faults, it has been decided to apply the bathtub curve only to these failure categories.

Finally, it is important to specify that the fleet size in this sensibility analysis will be five.

5.2.2.1 OUTPUTS

- **Time availability**:

Figure 47 shows how the time availability curves draw a curve inversely proportional to the distribution of failure rates applied to each scenario. In the intermediate range of the graph all scenarios are above the time availability of the constant ratio and at the outer extremes, they drop drastically due to the two critical stages of a turbine's service life. Table 14 shows the percentage increase or decrease of the time availability of the scenarios over the base case and in all cases there is a decrease from 0.63% to 1.08 %.

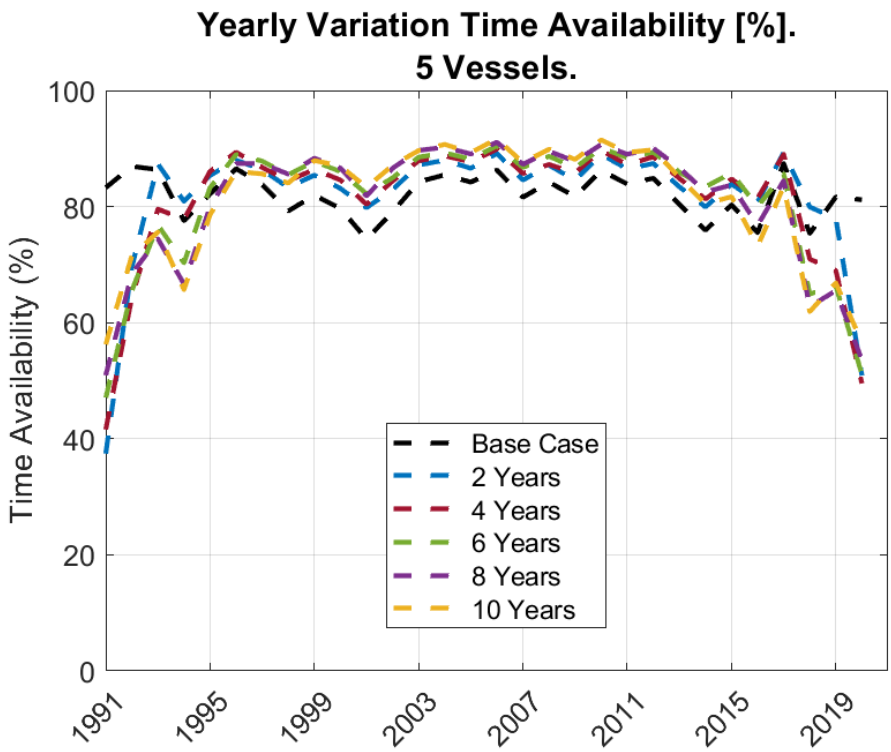

Figure 47. Time availability comparison for different years until maturity bathtub curves.

Table 14. Time availability for the different scenarios and comparison with base case.

Years until maturity	Mean Annual Time Availability	Time availability increase over constant failure rate
Constant	82.04 %	
2 Years	81.52 %	- 0.63 %
4 Years	81.16 %	- 1.07 %
6 Years	81.18 %	- 1.05 %
8 Years	81.15 %	- 1.08 %
10 Years	81.17 %	- 1.06 %

- **Power availability**:

As for the time availability analysis, in Figure 48 can be seen how the power availability curves draw a curve inversely proportional to the distribution of failure rates applied to each scenario. In the intermediate range of the graph all scenarios are above the power availability of the constant ratio and at the outer extremes, they drop drastically due to the two critical stages of a turbine's service life. Table 15Table 14 shows the percentage increase or decrease of the power availability of the scenarios over the base case and in all cases there is a decrease from 0.58% to 1.02 %.

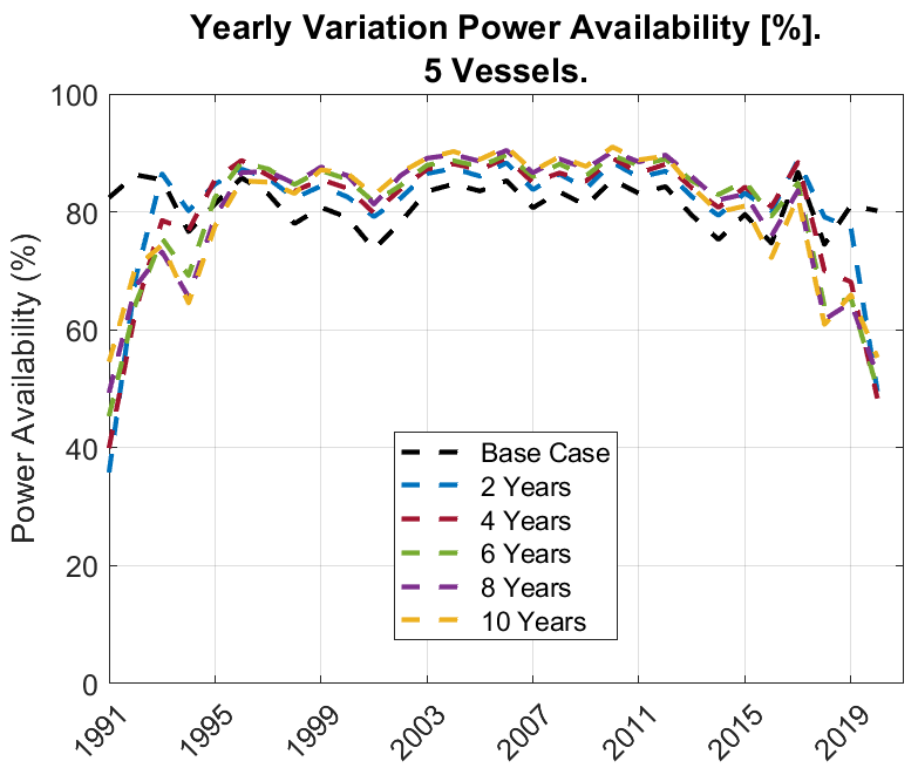

Figure 48. Power availability comparison for different years until maturity bathtub curves.

Table 15. Power availability for the different scenarios and comparison with base case.

Years until maturity	Mean Annual Power Availability	Power availability increase over constant failure rate
Constant	81.24 %	
2 Years	80.77 %	- 0.58 %
4 Years	80.42 %	- 1.01 %
6 Years	80.44 %	- 0.98 %
8 Years	80.41 %	- 1.02 %
10 Years	80.43 %	- 1.00 %

- **Total downtime**:

In Figure 49 can be seen how the total downtime curves draw a curve proportional to the distribution of failure rates applied to each scenario. In the intermediate range of the graph, all scenarios are below the total downtime of the constant ratio and at the outer extremes rise drastically due to the two critical stages of a turbine's service life. Table 16Table 14 shows the percentage increase or decrease of the power availability of the scenarios over the base case and in all cases there is an increase from 7.89% to 11.75 %.

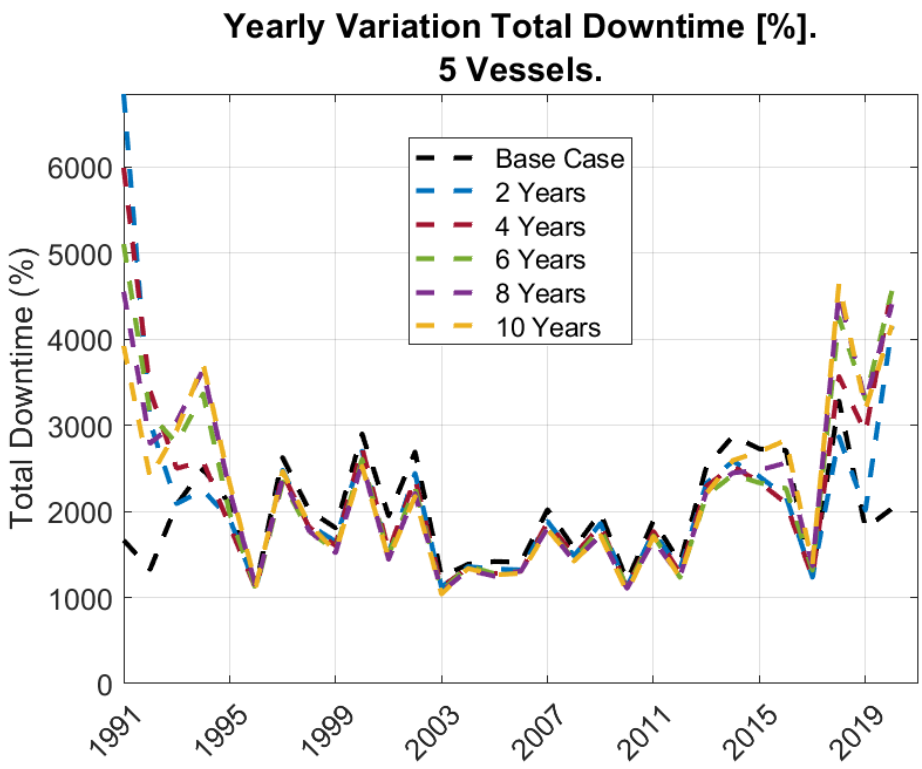

Figure 49. Total downtime comparison for different years until maturity bathtub curves.

Table 16. Total downtime for the different scenarios and comparison with base case.

Years until maturity	Mean Annual Total Downtime	Downtime increase over constant failure rate
Constant	1982.69 %	
2 Years	2139.12 %	+ 7.89 %
4 Years	2195.50 %	+ 10.73 %
6 Years	2208.60 %	+ 11.39 %
8 Years	2215.63 %	+ 11.75 %
10 Years	2199.22 %	+ 10.92 %

5.2.2.1 OPTIMIZATION OF THE NUMBER OF O&M VESSELS

Next, for the case of 6-years until maturity bathtub curve, an economic analysis on power production has been carried out.

With the price of MWh previously mentioned (130 €/MWh), the income has been calculated by multiplying the power production by the hours of the year and by the cost of the MWh to obtain the income received from the sale of the energy produced. The cost of the available vessels is subtracted from this income, assuming a cost of 4 million euros per vessel, in line with Section 5.2.1.1 Optimization of the number of O&M vessels

Of course, the cost of the vessel is not the only expense that the OWF has to undertake, but the rest of the expenses are assumed to be constant since they will have to be faced regardless of the number of vessels available to carry out the O&M activities.

The following figures show an analysis of the most profitable number of vessels for each year. The legend shows in green the highest value for each year and in red the lowest one. (The columns show the lifespan number of years) and the rows show the profit for that year depending on the variable number of vessels from 1 to 10. (See from Figure 50 to Figure 53).

It can be seen how the benefits present an inversely proportional distribution to the failure rate distribution, which is reasonable, since the higher the number of failures, the lower the availability of

the turbine to produce energy, so production will improve the more vessels we have to deal with repairs.

Years	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1_VESSEL	14.57	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-3.95	-3.80	-3.48	0.71	15.98	27.44	34.34	35.90	38.77	51.09	43.35	43.70	58.04	47.54	24.59	-1.12	-3.93	-4.00
2_VESSEL	23.14	1.22	57.68	107.07	191.34	231.14	234.59	226.82	239.80	217.22	214.46	226.95	208.04	244.45	248.02	246.29	228.19	232.18	239.18	244.67	228.45	248.32	236.87	196.89	226.71	167.76	197.78	124.72	76.68	-2.54
3_VESSEL	66.55	91.71	151.11	144.34	208.17	233.04	234.38	233.08	247.51	228.65	233.65	232.94	213.42	243.86	253.36	245.42	237.72	235.34	241.97	251.26	230.50	251.77	250.80	213.85	236.34	176.90	215.11	151.82	113.83	75.91
4_VESSEL	80.30	120.32	176.19	160.14	215.04	230.65	231.63	232.49	246.29	227.70	237.96	232.15	212.40	240.65	251.79	242.14	237.46	233.37	240.32	248.79	229.04	249.87	250.42	216.39	235.04	180.70	214.93	164.64	145.37	105.48
5_VESSEL	96.13	147.04	187.53	168.77	215.62	227.46	227.98	229.83	243.43	224.55	235.73	229.66	209.21	236.80	248.62	238.40	234.62	230.07	237.43	245.34	225.65	246.53	247.70	215.11	232.03	182.32	211.92	170.56	161.93	117.50
6_VESSEL	114.71	168.01	189.70	173.61	213.37	223.52	224.35	227.08	239.80	220.87	232.32	226.60	205.55	232.89	244.98	234.54	231.26	226.39	234.06	241.47	222.02	242.88	244.17	212.60	228.53	182.16	208.20	172.49	167.59	122.78
7_VESSEL	125.67	169.77	188.98	174.96	210.25	219.69	220.58	223.75	236.01	217.02	228.54	223.06	201.74	228.92	241.20	230.61	227.41	222.52	230.38	237.59	218.03	238.96	240.49	209.33	224.81	180.22	204.41	172.75	167.53	129.44
8_VESSEL	128.12	168.26	187.04	173.81	206.35	215.81	216.72	220.11	232.05	213.07	224.71	219.46	197.88	224.93	237.29	226.66	223.60	218.58	226.63	233.61	214.07	234.97	236.58	205.77	220.93	177.92	200.45	172.18	165.23	134.74
9_VESSEL	132.72	165.26	183.80	172.29	202.56	211.82	212.80	216.28	228.14	209.16	220.87	215.68	193.93	220.93	233.39	222.70	219.70	214.63	222.76	229.62	210.12	230.97	232.64	202.39	216.94	174.67	196.50	171.06	162.38	137.99
10_VESSEL	132.88	162.18	179.97	169.07	198.70	207.85	208.83	212.39	224.18	205.20	216.95	211.86	189.96	216.93	229.38	218.72	215.79	210.64	218.86	225.63	206.11	226.98	228.71	198.64	212.96	171.28	192.51	169.53	159.19	138.25

Figure 50. Profit calculations for a 6-year maturity bathtub curve.

Years	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1_VESSEL	14.57	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00	-4.00
2_VESSEL	23.14	1.22	57.68	107.07	191.34	231.14	234.59	226.82	239.80	217.22
3_VESSEL	66.55	91.71	151.11	144.34	208.17	233.04	234.38	233.08	247.51	228.65
4_VESSEL	80.30	120.32	176.19	160.14	215.04	230.65	231.63	232.49	246.29	227.70
5_VESSEL	96.13	147.04	187.53	168.77	215.62	227.46	227.98	229.83	243.43	224.55
6_VESSEL	114.71	168.01	189.70	173.61	213.37	223.52	224.35	227.08	239.80	220.87
7_VESSEL	125.67	169.77	188.98	174.96	210.25	219.69	220.58	223.75	236.01	217.02
8_VESSEL	128.12	168.26	187.04	173.81	206.35	215.81	216.72	220.11	232.05	213.07
9_VESSEL	132.72	165.26	183.80	172.29	202.56	211.82	212.80	216.28	228.14	209.16
10_VESSEL	132.88	162.18	179.97	169.07	198.70	207.85	208.83	212.39	224.18	205.20

Figure 51. Benefit analysis from year 1991 to 2000.

Years	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1_VESSEL	-4.00	-4.00	-3.95	-3.80	-3.48	0.71	15.98	27.44	34.34	35.90
2_VESSEL	214.46	226.95	208.04	244.45	248.02	246.29	228.19	232.18	239.18	244.67
3_VESSEL	233.65	232.94	213.42	243.86	253.36	245.42	237.72	235.34	241.97	251.26
4_VESSEL	237.96	232.15	212.40	240.65	251.79	242.14	237.46	233.37	240.32	248.79
5_VESSEL	235.73	229.66	209.21	236.80	248.62	238.40	234.62	230.07	237.43	245.34
6_VESSEL	232.32	226.60	205.55	232.89	244.98	234.54	231.26	226.39	234.06	241.47
7_VESSEL	228.54	223.06	201.74	228.92	241.20	230.61	227.41	222.52	230.38	237.59
8_VESSEL	224.71	219.46	197.88	224.93	237.29	226.66	223.60	218.58	226.63	233.61
9_VESSEL	220.87	215.68	193.93	220.93	233.39	222.70	219.70	214.63	222.76	229.62
10_VESSEL	216.95	211.86	189.96	216.93	229.38	218.72	215.79	210.64	218.86	225.63

Figure 52. Benefit analysis from year 2001 to 2010.

Years	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1_VESSEL	38.77	51.09	43.35	43.70	58.04	47.54	24.59	-1.12	-3.93	-4.00
2_VESSEL	228.45	248.32	236.87	196.89	226.71	167.76	197.78	124.72	76.68	-2.54
3_VESSEL	230.50	251.77	250.80	213.85	236.34	176.90	215.11	151.82	113.83	75.91
4_VESSEL	229.04	249.87	250.42	216.39	235.04	180.70	214.93	164.64	145.37	105.48
5_VESSEL	225.65	246.53	247.70	215.11	232.03	182.32	211.92	170.56	161.93	117.50
6_VESSEL	222.02	242.88	244.17	212.60	228.53	182.16	208.20	172.49	167.59	122.78
7_VESSEL	218.03	238.96	240.49	209.33	224.81	180.22	204.41	172.75	167.53	129.44
8_VESSEL	214.07	234.97	236.58	205.77	220.93	177.92	200.45	172.18	165.23	134.74
9_VESSEL	210.12	230.97	232.64	202.39	216.94	174.67	196.50	171.06	162.38	137.99
10_VESSEL	206.11	226.98	228.71	198.64	212.96	171.28	192.51	169.53	159.19	138.25

Figure 53. Benefit analysis from year 2011 to 2020.

In Table 17 different combinations of vessel numbers have been selected throughout the lifespan.

First of all, we must not forget that the main purpose of this analysis is to establish the consequences of defining a variable or constant failure rate. For this reason, the second column shows the benefits obtained annually for constant failure rates and a fleet size of five vessels, since this would be the optimal option obtained from the analysis in section 5.2.1.1.

Moreover, in the column: "5 vessels" in the variable failure ratio section, the benefits obtained if considering that the variable failure ratio is not taken into account and the 5 vessels are kept constant are shown. At the bottom of the table it can be seen that there would be 63 million euros of profit if it is design for constant failure ratio and finally results that the components respond to a 6-year until maturity failure distribution.

The max profit columns show, both for the constant failure rate and the variable failure rate, the number of vessels with the highest profit for each year (in green in the figures above) and the corresponding profit in million euros to the right of it. At the end of the table, both values are compared with the constant failure rate and five constant vessels. It is obtained that in the case of constant failure rate with the choice of vessels that provide the maximum performance only 35 million euros more would be generated. In contrast, if the failure rate distribution is characterized along lifespan for the later implementation of the optimal number of vessels analysis, 127 million extra euros could be earned.

Finally, the last column of the table refers to the idea that the max profit option will not be realistic. In a posteriori analysis, it is possible to know when a failure will occur or what meteocean conditions are going to be experienced that year, but in reality, these are not variables that can be controlled with such a high level of detail. Therefore, it is possible to select a constant number of vessels in the case of constant failure rates or an estimated curve inversely proportional to the failure distribution in the case of variable failure rate (selected curve). This curve is an estimate vessel combination inversely proportional to the failure rate distribution although it is not the only possible solution of this type. It also shows the number of vessels corresponding to each year and the benefits associated to that fleet size choice, which in this example results in an extra 115 million euros over the constant failure rate case. In any case, it is clear that the perceived variations between implementing

or not the variable ratio for the design of the O&M strategy show the importance of going deeper into this research for simulating the OWF more accurately.

Table 17. Comparison of benefits between different O&M strategies.

	Constant Failure Rate			6 years until maturity bathtub curve				
Years	**5 Vessels [Million €]**	**Max profit [Million €]**		**5 Vessels [Million €]**	**Max profit [Million €]**		**Selected curve [Million €]**	
1991	211.5	4 Vessels	211.6	96.1	10 Vessels	132.9	9 Vessels	132.7
1992	213.2	4 Vessels	215.5	147.0	7 Vessels	169.8	7 Vessels	169.8
1993	217.0	4 Vessels	218.7	187.5	6 Vessels	189.7	7 Vessels	189.0
1994	192.2	6 Vessels	192.3	168.8	7 Vessels	175.0	7 Vessels	175.0
1995	211.9	5 Vessels	211.9	215.6	5 Vessels	215.6	5 Vessels	215.6
1996	219.5	3 Vessels	222.7	227.5	3 Vessels	233.0	3 Vessels	233.0
1997	214.4	3 Vessels	218.6	228.0	2 Vessels	234.6	3 Vessels	234.4
1998	208.7	4 Vessels	209.4	229.8	3 Vessels	233.1	3 Vessels	233.1
1999	223.5	5 Vessels	223.5	243.4	3 Vessels	247.5	3 Vessels	247.5
2000	202.4	5 Vessels	202.4	224.6	3 Vessels	228.6	3 Vessels	228.6
2001	208.4	6 Vessels	209.4	235.7	4 Vessels	238.0	3 Vessels	233.6
2002	208.8	5 Vessels	208.8	229.7	3 Vessels	232.9	3 Vessels	232.9
2003	196.3	5 Vessels	196.3	209.2	3 Vessels	213.4	3 Vessels	213.4
2004	224.9	3 Vessels	228.5	236.8	2 Vessels	244.4	3 Vessels	243.9
2005	235.2	4 Vessels	236.3	248.6	3 Vessels	253.4	3 Vessels	253.4
2006	225.0	3 Vessels	228.3	238.4	2 Vessels	246.3	3 Vessels	245.4
2007	217.0	5 Vessels	217.0	234.6	3 Vessels	237.7	3 Vessels	237.7
2008	215.6	4 Vessels	216.6	230.1	3 Vessels	235.3	3 Vessels	235.3
2009	220.2	4 Vessels	221.2	237.4	3 Vessels	242.0	3 Vessels	242.0
2010	232.3	4 Vessels	233.4	245.3	3 Vessels	251.3	3 Vessels	251.3
2011	211.1	4 Vessels	212.7	225.6	3 Vessels	230.5	3 Vessels	230.5
2012	231.5	4 Vessels	232.2	246.5	3 Vessels	251.8	3 Vessels	251.8
2013	228.2	5 Vessels	228.2	247.7	3 Vessels	250.8	3 Vessels	250.8
2014	190.1	5 Vessels	190.1	215.1	4 Vessels	216.4	3 Vessels	213.9
2015	214.2	4 Vessels	214.9	232.0	3 Vessels	236.3	3 Vessels	236.3
2016	167.3	6 Vessels	169.3	182.3	5 Vessels	182.3	4 Vessels	180.7
2017	217.5	3 Vessels	222.4	211.9	3 Vessels	215.1	4 Vessels	214.9
2018	204.5	6 Vessels	204.8	170.6	7 Vessels	172.8	6 Vessels	172.5
2019	212.2	4 Vessels	212.7	161.9	6 Vessels	167.6	6 Vessels	167.6
2020	214.6	5 Vessels	214.6	117.5	10 Vessels	138.3	9 Vessels	138.0
Σ Income	6388.9		6424.2	6325.5		6516.3		6504.6
Profit over Constant Failure rate and 5 vessels			35.3 M€	63.5 M€		127.4 M€		115.7 M€

The power availability has also been analysed in the following table. For this purpose, the power availability corresponding to the same number of vessels selected in the economic analysis has been chosen for each year. See Table 18.

It can be seen that the power availability decreases in some cases and increases in others with respect to the constant case with five constant vessels. This is because the average number of vessels over the lifetime in the cases where power availability decreases in lower than five and as already seen in Figure 41 the lower the number of vessels the lower the power availability. For the two cases on the right, the power availability increases because at the beginning and at the end of the lifetime a large fleet size is required although in the middle section only three vessels are contracted.

Table 18. Comparison of power availability between different O&M strategies.

Years	Constant Failure Rate			6 years until maturity bathtub curve				
	5 Vessels [%]	Max profit [%]		5 Vessels [%]	Max profit [%]		Selected curve [%]	
1991	82,42	4 Vessels	81,19	45,32	10 Vessels	63,14	9 Vessels	61,85
1992	86,29	4 Vessels	85,77	64,40	7 Vessels	74,35	7 Vessels	74,35
1993	85,44	4 Vessels	84,69	75,52	6 Vessels	77,59	7 Vessels	78,70
1994	76,65	6 Vessels	78,06	69,19	7 Vessels	73,76	7 Vessels	73,76
1995	81,33	5 Vessels	81,33	82,46	5 Vessels	82,46	5 Vessels	82,46
1996	85,77	3 Vessels	84,29	88,36	3 Vessels	87,61	3 Vessels	87,61
1997	83,10	3 Vessels	81,97	87,28	2 Vessels	85,69	3 Vessels	86,84
1998	78,01	4 Vessels	76,92	84,64	3 Vessels	83,06	3 Vessels	83,06
1999	80,78	5 Vessels	80,78	87,01	3 Vessels	85,78	3 Vessels	85,78
2000	79,03	5 Vessels	79,03	85,53	3 Vessels	84,41	3 Vessels	84,41
2001	73,66	6 Vessels	75,02	81,65	4 Vessels	81,15	3 Vessels	78,86
2002	78,25	5 Vessels	78,25	84,47	3 Vessels	83,02	3 Vessels	83,02
2003	83,49	5 Vessels	83,49	87,93	3 Vessels	86,61	3 Vessels	86,61
2004	84,71	3 Vessels	83,35	88,68	2 Vessels	87,33	3 Vessels	88,39
2005	83,53	4 Vessels	82,67	87,69	3 Vessels	86,67	3 Vessels	86,67
2006	85,30	3 Vessels	83,74	89,68	2 Vessels	88,32	3 Vessels	89,36
2007	80,70	5 Vessels	80,70	85,98	3 Vessels	84,54	3 Vessels	84,54
2008	83,40	4 Vessels	82,45	88,10	3 Vessels	87,20	3 Vessels	87,20
2009	81,07	4 Vessels	80,16	86,12	3 Vessels	85,07	3 Vessels	85,07
2010	85,42	4 Vessels	84,56	89,54	3 Vessels	88,93	3 Vessels	88,93
2011	83,13	4 Vessels	82,38	87,90	3 Vessels	86,89	3 Vessels	86,89
2012	84,29	4 Vessels	83,33	88,98	3 Vessels	88,11	3 Vessels	88,11
2013	79,39	5 Vessels	79,39	85,23	3 Vessels	83,81	3 Vessels	83,81
2014	75,31	5 Vessels	75,31	82,93	4 Vessels	82,10	3 Vessels	80,07
2015	79,57	4 Vessels	78,48	85,19	3 Vessels	84,00	3 Vessels	84,00
2016	74,69	6 Vessels	76,49	79,28	5 Vessels	79,28	4 Vessels	77,58
2017	86,73	3 Vessels	85,75	84,90	3 Vessels	83,36	4 Vessels	84,58
2018	74,47	6 Vessels	75,86	63,97	7 Vessels	67,20	6 Vessels	65,84
2019	81,07	4 Vessels	79,96	65,37	6 Vessels	68,48	6 Vessels	68,48
2020	80,19	5 Vessels	80,19	49,90	10 Vessels	62,28	9 Vessels	60,97
Average	81.24		80,85	80,44		81,41		81,26
Increase over Constant Failure rate and 5 vessels			- 0.48 %	- 0.99 %		+ 0.21 %		+ 0.03 %

The same analysis could be performed for another vessel cost or other failure rate distribution to derive the corresponding optimum on the O&M strategy.

6 CONCLUSIONS AND FUTURE WORK

Based on the gaps identified on the O&M simulator, INGEOCEAN numerical model, a set of improvements were conceptualized and implemented in order to be able to deep into the importance of key elements like failure rates variability and vessels fleet size. Based on them, a detailed analysis of different failure rates strategies, as well as vessels fleet policies applied to an offshore wind farm in the Galician coast.

On an Offshore Wind Farm in early-planning phase located in San Cibrao, Galicia and consisting of 30 turbines of 15 MW, a base case has been generated for the project. This base case has been conveniently explained and its main characteristic is that the failure rates for all types of faults are constant.

On this base case, a sensitivity analysis has been carried out on the number of vessels to measure the impact on three key indicators in O&M, such as time availability, power availability and total downtime. With this and an economic study on the increase in profits obtained with each contracted vessel, the conclusion has been drawn that, assuming that the cost of a vessel is less than 4 million euros, five is the most suitable number of vessels for our scenario.

On the other hand, several studies have found that component failure rates are not constant along the lifespan but vary according to a bathtub curve distribution. This project has analysed the impact that different failure curves have on the three indicators mentioned above.

It has been found that they do not have a great impact in the intermediate stage (maturity stage) but this must be taken into account for the extremes when the faults are on the increase. A similar analysis to that carried out for the base case and the optimum number of vessels is repeated for the 6-year time to maturity bathtub curve case, again assuming a vessel cost of 4 million euros.

With this second analysis it has been possible to notice that if a constant number of vessels is used for the whole lifespan, the gains between understanding the failure rate of a component in detail or not is minor (1 million euros extra per year). However, if knowing the non-constant failure rate distribution and the number of vessels is adjusted to the optimum each year, benefits of up to 127 million euros can be obtained during the lifespan or, in other words, an extra 4.2 million euros per year.

This result highlights the need to study in detail the failure rates of the different components, since more accurate information will allow us to carry out more realistic simulations and consequently design the O&M strategy that maximises profits.

Overall, it has been demonstrated that Ingeocean is a useful tool for the evaluation and design of the maintenance strategy of an OWF.

As a proposal for future work, the possibility of varying the number of vessel available in the model at different stages of the lifespan is proposed to be able to correctly compute the pending faults when changing from one fleet size to another. Currently it only allows simulating a constant number of vessels.

Another potential improvement option would be to include cost values in the model and to calculate the OPEX internally without having to do any post-processing to obtain it.

It would also be considered the option of including a module that performs the optimisation analysis of the number of vessels like the one carried out in this project but internally.

An additional line of improvement would be to contemplate different types of contracts for the vessels and not to have all of them under the same conditions, which could be quite convenient according to the requirements of the OWF.

A more long-term line of action would be to carry out a study on the possible correlation between higher wave and wind energy flux direction and turbine faults, as well as to study whether there is a higher concentration of faults in more severe metocean periods (mainly from October to March). In this way, a more realistic distribution of faults can be made instead of maintaining the current version of a uniform distribution throughout the year. Such a study is quite challenging to be performed as the offshore wind industry is very recent and there is hardly any data available.

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